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SOME STUDIES OF NEW ZEALAND QUATERNARY PYROCLASTIC ROCKS

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SCOPE OF INVESTIGATION

This study is concerned with the identification and dating of Quaternary pyroclastic rocks erupted from the central North Island, New Zealand. The following aspects are specifically considered.

1) Assessment of the potential of using dominant ferromagnesian assemblage in conjunction with elemental abundances in titanomagnetite as a means of rapid identification of pyroclastic rocks.

2) Adaption of the fission-track technique for dating small amounts of glass shards (< 200 milligrams) over the time range of Upper Pliocene to the lower range of ^{14}C dating (c. 30,000 yrs).

3) Application of fission-track dating to establish an absolute chronology for ignimbrite eruptions in the central North Island, and to correlate ashes in deep-sea cores previously dated using paleomagnetic methods (Ninkovich 1968), with these ignimbrites.

NOMENCLATURE

Pyroclastic Nomenclature

Nomenclature in the pyroclastic rocks has become confused during the last decade largely because of the different aims of the studies undertaken. Healy et al (1964), Vucetich and Pullar (1969) and others have been concerned with mapping such rocks over a wide area and hence require terms which describe the units throughout their distribution. Ewart (1968), Cole (1970a) and Kohn (1970), however, have described petrographic and chemical aspects of pyroclastic rocks. These authors require terms suitable for description at a particular locality.

In this thesis it is necessary to use terms which can be used when studying pyroclastic rocks from stratigraphic, petrographic and chemical aspects. The following definitions of terms are thus outlined and a brief discussion of the use of more problematical terms is given.

Pyroclastic - Wentworth and Williams (1932) defined "pyroclastic" as "an adjective applied to rocks produced by explosive or aerial ejection of material from a volcanic vent." As such, the term is interpreted as including deposits formed from explosive "air-fall" eruptions and from nuées ardentes. The definition in the A.G.I. Glossary (1960) of "detrital volcanic materials" is misleading as it implies mechanical breakdown of volcanic rocks after deposition.

Tephra - A term coined by Thorarinsson (1954) for "all the clastic volcanic material which during an eruption is transported from the crater through the air, corresponding to the term lava to signify all the molten material flowing from the crater." It is a particularly useful term for general descriptions of unconsolidated pyroclastic deposits, as the term implies no particular grain size. The main problem is whether the term should be restricted to airfall pyroclastic deposits or used for both airfall and pyroclastic flow deposits (the products of nuées ardentes). In view of Thorarinsson's recent paper referring to tephra-flows (Thorarinsson 1969), it is considered that pyroclastic flow deposits can be called "tephra" if unconsolidated. Where an airfall origin can clearly be established the deposit can be called "tephra-fall", where pyroclastic flow origin is evident "tephra-flow".

Tephra may be subdivided according to grain size into ash, lapilli, or blocks (Wentworth and Williams 1932). The size limits of these units were later modified by Fisher (1961) to conform with sedimentological terms (see Table 1, below).

Tuff, Agglomerate - Consolidated pyroclastic rocks in which individual fragments retain their original form (i.e., have not been welded). Divisions based on size are given below.

Size (in mm)	Unconsolidated	Consolidated
> 64	Blocks/Bombs	Breccia/Agglomerate
64 - 2	Lapilli	Lapilli Tuff
2 - 0.063	Coarse Ash	Coarse Tuff
< 0.063	Fine Ash	Fine Tuff

Table 1 - Subdivision of pyroclastic rocks according to grain size (Wentworth and Williams 1932, modified by Fisher 1961).

Pumice - A natural glass froth in which the volume of air space approaches, equals or exceeds the volume of glass (Heinrich 1956, p.41). Pumice would therefore generally float in water.

Ignimbrite - The term "ignimbrite" was first used by Marshall (1932) to describe the extensive "rhyolitic" sheets of the North Island, which he considered to have formed by a type of "nuée ardente" eruption. In a later paper (Marshall 1935) he gives a definition of the term as; "Igneous rocks of acid or intermediate composition which have been formed from material that has been ejected from orifices in the form of a multitude of highly incandescent particles which were mainly of minute size." Since 1935, the term has been used in various ways. Some authors (e.g., Cotton 1944) used it as synonymous with welded tuff, while others (e.g., Beavon et al, 1961) include both welded tuff and non-welded tuff or sillar. This controversy over the degree of welding necessary for a rock to be called "ignimbrite" is widespread, and depends on whether the key features of an ignimbrite are the "nuée ardente eruption" origin or the presence of "highly incandescent particles". It is desirable to separate descriptive and genetic terms, and in view of Marshall's (1935) definition, it is considered that the non-genetic feature is the most important and that some degree of welding should be present in an ignimbrite. The term ignimbrite is therefore a rock unit name (including welded portions) with genetic significance (dominantly pyroclastic flow in origin).

Deposits giving greatest problems of nomenclature are those formed by smaller nuées ardentes. The resultant deposits are frequently not welded and as such should not be called ignimbrites. In New Zealand such non-welded deposits are called "pumice breccia" (a descriptive term). This term implies both angularity, coarse grain size and consolidation (Table 1). Yet some unconsolidated deposits (e.g. Oruanui Breccia) grade into finer grained deposits (dominantly ash size) away from their source. A better general term for describing the complete unit would be "tephra-flow".

In order to avoid confusion, where a unit has previously been formally named, that name will be retained in this thesis even if it does not conform to the above usage of nomenclature.

Petrographic and Chemical Nomenclature

The variety of modal and chemical parameters assigned to calc-alkaline volcanic rocks (e.g., Williams et al 1954, p. 12, Ewart and Stipp 1968, Taylor et al 1969, Chayes 1970, Wilkinson 1971 and Irvine and Baragar 1971) reflects a lack of agreement among workers on definite nomenclature.

In this study the classification within the unweathered andesite-dacite-rhyolite sequence is made on the basis of SiO_2. Andesites contain 53-63% SiO_2 and generally do not contain modal quartz. Dacite contains 63-70% SiO_2 and rhyolite 70-77% SiO_2 with Na_2O+K_2O=6.6-8.2% and Na_2O/K_2O ratio >1. Ewart and Stipp (1968) classified dacites as containing 64-68% SiO_2 with a small distinct gap between dacite and rhyolite. Although rhyodacite may be considered an appropriate term for rocks with 68-70% SiO_2 it has not been considered here because there is no consistency in the use of the term in the literature (Irvine and Baragar 1971). Dacite is therefore extended from Ewart and Stipp's upper limit from 68% to 70% SiO_2. The lower limit of 63% SiO_2 for dacite is according to Taylor et al (1969) and Duncan (1970a). Duncan (1970a) has also shown that a mineralogical criterion which closely corresponds to the 63% SiO_2 andesite-dacite dividing line is the presence (dacite) or absence (andesite) of modal quartz.

It should be emphasised that all chemical boundaries are gradational. Duncan (1970a) for example, has shown that analyses within one volcano (Mt. Edgecumbe) may span the andesite-dacite boundary.

SUMMARY OF THE GEOLOGY AND VOLCANIC HISTORY OF THE TAUPO VOLCANIC ZONE

Details of the structure, distribution of Quaternary volcanic rocks and volcanic mechanisms controlling eruptions in the Taupo Volcanic Zone (Fig 1) calc-alkaline province have been given by Healy (1962, 1964), Healy et al (1964), Grindley (1960), Thompson (1964) and Modriniak and Studt (1959). Accounts of various aspects of the petrology and petrochemistry are given by Steiner (1958), Clark (1960a,b), Ewart (1963, 1965a, 1966, 1967a, 1968, 1969, 1971a), Ewart and Stipp (1968), Ewart et al (1968a), Ewart and Taylor (1969), Ewart et al (1971), and Cole (1970a,b,c, 1973).

The Taupo Volcanic Zone extends northeast for 250 km from the volcanoes of National Park in the centre of the North Island to White Island in the Bay of Plenty, reaching a maximum width of 40 km. Rhyolitic volcanism (Pleistocene-Recent) is dominant, forming lavas and domes, voluminous welded ignimbrites (and unwelded "pumice breccias") and as blanketing airfall tephra deposits. Healy (1962) estimates the order of 16,700 km^3 of rhyolitic material. Andesitic lavas (totalling about 83 km^3 of outcrop), have their main occurrence at the extreme ends of the Taupo Volcanic Zone. Basaltic outcrops amount to no more than 42 km^3 and their vents appear to be located where the NNE trending regional faults cross caldera structures (Cole 1972). With two exceptions the basaltic outcrops occur as isolated flows and scoria cones distributed throughout the area. The two exceptions are the Matahi Basaltic Tephra (Pullar and Nairn 1972) which conformably underlies rhyolitic deposits ^{14}C dated at c. 44,000 yrs B.P. and the scoriaceous Tarawera ash and lapilli erupted violently from Mt. Tarawera (previously rhyolitic) in 1886. Dacitic lavas occur as isolated domes distributed throughout the region.

The rhyolitic volcanism appears to have been largely concentrated in four centres, occupying the central 135 km of the Taupo Volcanic Zone (Healy 1962, 1964 and Thompson 1964). The centres, each apparently controlled by ring structures, are from south to north (Fig 1), the Lake Taupo Volcanic Centre, Maroa Volcanic Centre, Rotorua Volcanic Centre and

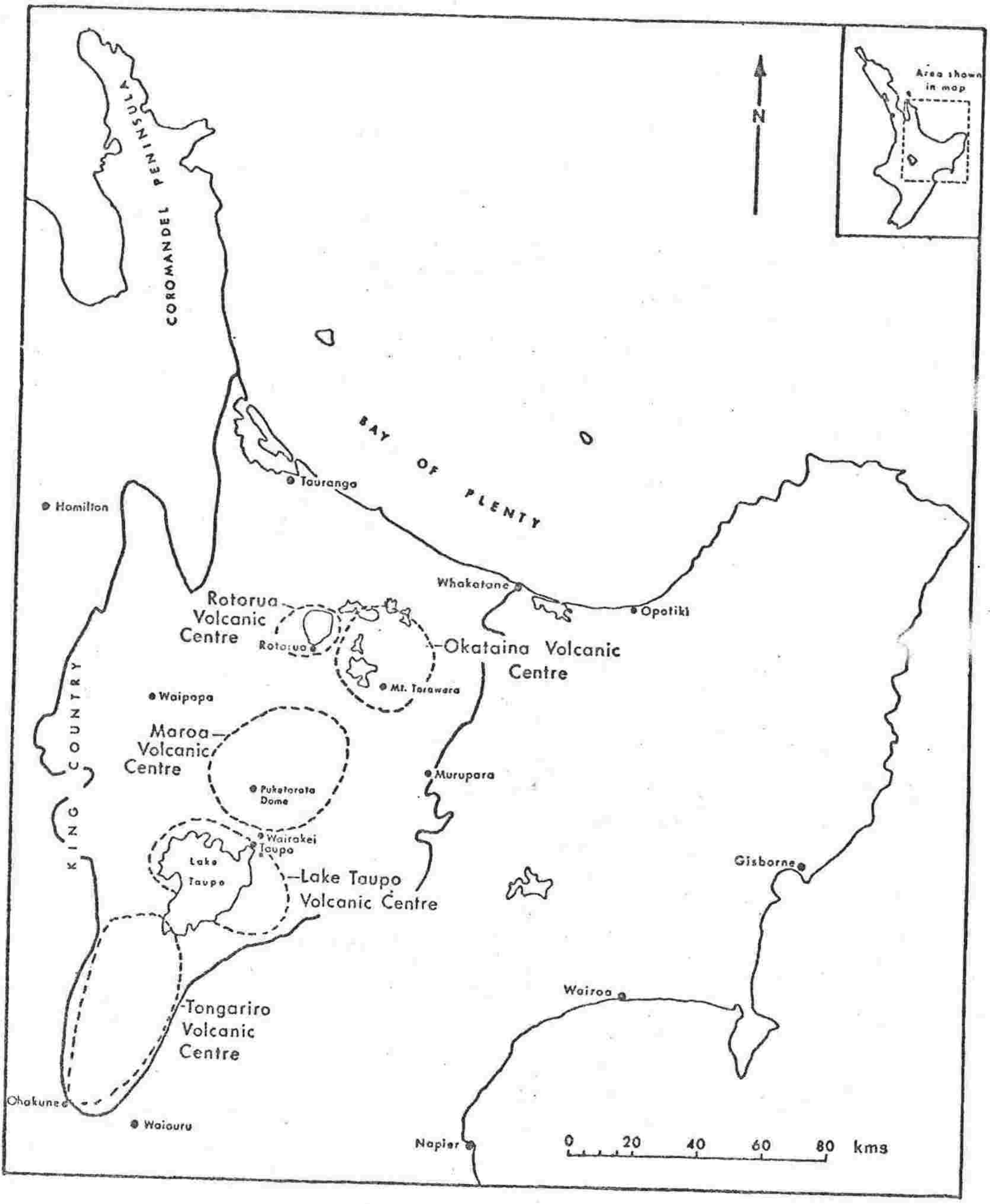

Fig. 1. - The Taupo Volcanic Zone and surrounding area. The location of the Tongariro, Lake Taupo, Maroa, Rotorua and Okataina Volcanic Centres (dashed lines) is also shown.

Okataina Volcanic Centre. Each centre is marked by concentrations of rhyolitic domes and is flanked by extensive ignimbrite plateaux. The generalised volcanic succession from each centre (with overlap between centres) is believed to be (after Ewart and Stipp 1968): 1) extensive welded ignimbrite deposits (possibly from fractures marking the periphery of the centres); 2) an older phase of viscous rhyolite lava domes; 3) localised glowing avalanche (nuée ardente) eruptions giving rise to unwelded pumice deposits ("pumice breccias"); 4) a younger resurgent phase of rhyolite domes and flows, frequently erupted within the central portions of the volcanic centres; 5) violent tephra-fall eruptions, resulting in deposits which blanket much of the central and southern North Island. The most extensive of these deposits were erupted from the Lake Taupo Volcanic Centre and to a lesser extent from the Okataina Volcanic Centre.

A study of the pyroclastic rocks produced during phases 1, 3 and 5 which have been spread over an area of at least 45,000 km^2, comprises the bulk of work reported in this thesis.

Detailed mapping of Late Quaternary tephras (phase 5) aided by ^{14}C dating has provided a time scale for eruptions over the last 44,000 yrs B.P. (Healy, Vucetich and Pullar 1964, Vucetich and Pullar 1969, 1973) and a number of papers (e.g., Wellman 1962, Pullar 1959, 1965, 1967, 1970, Vucetich and Pullar 1963, Cowie 1964, Vucetich 1968, Rhea 1968, and Nairn 1972) have indicated the importance of developing methods for rapid identification of these tephras as an aid for dating geological, archaeological and paleopedological events. Studies on the ^{14}C dated deposits are thus more advanced than on the underlying consolidated volcanics, which have in the past only had ages inferred from the relationship of some of the volcanics to sediments dated in the marginal areas by fossils, by paleomagnetic studies on deep sea core samples and ignimbrites on land, and a few K-A dates on lavas.

Because of the different levels of knowledge about the >44,000 yrs B.P. pyroclastics and the younger tephras (<44,000 yrs B.P.), which are underlain by a widespread paraconformity (Vucetich and Pullar 1969), studies on these deposits are treated separately in this thesis.

PART I

STUDIES OF POST C. 44,000 YR B.P. TEPHRAS ERUPTED FROM THE CENTRAL NORTH ISLAND, NEW ZEALAND.

A. METHODS OF TEPHRA IDENTIFICATION

INTRODUCTION

The development of volcanic "ash" studies in New Zealand can be traced through three broad periods (Jeune 1970).

During the late 19th century the extensive pumice deposits surrounding Lake Taupo received considerable comment (Crawford1875, Smith 1876 and Cussen 1887). Thomas (1887) recognised a covering of younger andesitic ash from Mts. Tongariro and Ruapehu overlying the pumice from Taupo and in his 1888 report on the eruption of Mt. Tarawera in 1886, Thomas provided a valuable description of the eruption and the deposits resulting from it.

Tephra deposits received only cursory attention during the following years until soil surveys initiated as part of the research effort into bush sickness demonstrated a relationship between incidence of the disease and soil derived from tephra (Aston 1926). Extended soil surveys followed (Grange 1929, 1931, 1937, Taylor 1930, 1933, Grange and Taylor 1931, 1932) during the course of which many important soil forming tephras were named, described and mapped. On the basis of mineral studies, contributions were recognised from four recently active volcanic centres; Taupo, Rotorua, Tongariro National Park and Mt. Egmont.

In the last 20 years, with many new cuttings being exposed during the course of road construction, attention has shifted to more deeply buried tephras not forming part of the present soil. Detailed stratigraphic studies (Baumgart 1954, Baumgart and Healy 1956, Healy, Vucetich and Pullar 1964, Vucetich and Pullar 1963, 1969, 1973, Ward 1967 and Nairn 1972) supplemented by ^{14}C age determinations have provided the basis of a reliable regional stratigraphy which now forms a framework into which more specialised studies may be fitted. Table 2 summarises the stratigraphic succession, chronology and composition of tephras erupted from the Taupo Volcanic Zone over the past c. 44,000 yrs B.P.

Table 2. - Stratigraphy and chronology of < c. 44,000 yr B.P. tephras erupted from Taupo Volcanic Zone.

*KEY TO REFERENCE TO NAME AND AGE (see over page)

1. Thomas (1888).
2. Grange (1929).
3. Vucetich and Pullar (1964).
4. Wellman (1962) and Wellman (pers. comm.).
5. Duncan (1970b).
6. Leahy (1971).
7. Green (1963).
8. Cole (1970a).
9. Baumgart and Healy (1956).
10. Healy (1964).
11. Healy (1965).
12. Baumgart (1954).
13. Pullar and Heine (1971).
14. Vucetich and Pullar (1973).
15. Grange (1937).
16. Taylor (1953).
17. Gibbs (1968).
18. McCraw and Whitton (1971).
19. Grant-Taylor and Rafter (1962).
20. (see Appendix III).
21. Topping (pers. comm.).
22. Grange (1931).
23. Lloyd (1972).
24. Vucetich and Pullar (1963).
25. Vucetich and Pullar (1969).
26. Berry (1928).
27. Cowie (1964).
28. Nairn 1971).
29. Ewart and Healy (1965a).
30. Nairn and Kohn (in press - see section B, Part 1).
31. Healy and Ewart (1965).
32. Thompson (1968).
33. Nairn (1972).
34. Pullar and Nairn (1972).

*References are given in Part 3.

T E P H R A	VOLCANIC CENTRE (SOURCE)	^{14}C AGE (YRS BEFORE 1950)	N.Z. ^{14}C NO.	*REFERENCE TO NAME AND AGE	N O T E S A N D C O R R E L A T I O N
Tarawera ^{B**}	Okataina (Mt. Tarawera)	-	-	1,2,3.	Historical eruption in 1886, also includes Rotomahana Mud.
Loisels Pumice ^{A,D} (distinctly banded, light bands - dacite dark bands - andesite	Unknown, may have been erupted from sea-mounts near White Island ^{5}	> 421 ± 40 > 519 ± 41 < 799 ± 40 < 640 ± 50 < 925 ± 46	1169 631 396 354 651	4,5,6,7.	Sea-rafted coastal deposits on fore-dunes.
Kaharoa ^{R}	Okataina (Mt. Tarawera)	930 ± 70	10	2,3,8,24.	
Upper Taupo Pumice ^{R}	Taupo			9,10,11.	Taupo sub-group member 1 (Tsg 1). nuées ardentes deposits of Taupo Pumice Formation.
Taupo Rhyolite Block member ^{R}	Taupo			9,10,11.	Tsg 2 of Taupo Pumice Formation.
Taupo Lapilli ^{R}	Taupo	1,819 ± 17	statistical mean of many dates ^{10}	3,10,11,12.	Tsg 3 " " " " .
Rotongaio Ash ^{R}	Taupo			10,11,12.	Tsg 4 " " " " .
Putty Ash ^{R}	Taupo			10,11.	Tsg 5 " " " " .
Hatepe Lapilli ^{R}	Taupo	1,900 ± 60	168	10,11,12.	Tsg 6,7,8 " " " " .
Leigh Pumice	Unknown, may have been erupted from sea-mounts near White Island ^{5}			4.	Sea-rafted coastal deposits.
^{14}Mapara ^{R}	Taupo	> 2,010 ± 60 < 2,150 ± 48 2,304 ± 90	1068 1069 weighted mean of two dates ^{10}	10,11,12,13,14.	Tsg 9-10.
^{14}Whakaipo ^{R}	Taupo	2,800 ± 100 > 2,670 ± 50 < 2,730 ± 60	182 1070 1071	10,11,12,13,14.	Tsg 11-13.
Waimihia Lapilli ^{R}	Taupo	3,420 ± 70 < 3,440 ± 70 > 3,170 ± 80 < 3,440 ± 80	179	3,9,10,11,12,13.	Tsg 14-15.

Rotokawau ^{B,R}	Okataina (Lake Rotokawau, Roto-Ngata and Roto-Atua Craters)[15]	-	-	2,13,15,24.	Rotokawau basalt ash and scoria.
Whakatane ^{R}	Okataina	5,180 ± 80	1066	3,16,24.	Lower part of Whakatane Ash, and Tsg 16a and b.
Whangamata ^{P}	Probably erupted from Mayor Island[18]	< 5,370 ± 90	333	16,17,18,19.	Distribution localised around Whangamata. ^{14}C date from peat on Hauraki Plains underlying an ash inferred to be Whangamata Ash.
^{14}Hinemaiaia ^{R}	Taupo	< 6,345 ± 30 > 6,390 ± 120 < 6,190 ± 70	427 1137 1247	3,10,11,13,14.	Tsg 16c and d.
Mamaku ^{R}	Okataina	7,050 ± 77	1152	2,3,24.	Formerly upper part of Mamaku Rhyolite pumice (ash)[2].
Rotoma ^{R}	Okataina	7,330 ± 235	1199	2,3,24.	Formerly lower part of Mamaku Rhyolite pumice (ash)[2]. Also correlates with Tsg 16e.
^{14}Opepe ^{R}	Taupo	8,850 ± 1,000	185	10,11,12,14.	Tsg 17-18.
^{14}Poronui ^{R}	Taupo	> 9,560 ± 100 < 9,700 ± 210 < 9,780 ± 170	1335 1373 1372	10,11,12,14, 20,21.	Tsg 19-22.
^{20}Papanetu ^{R}	Taupo (Kuhurua Dome)	> 9,700 ± 210 > 9,780 ± 170 < 9,790 ± 160	1373 1372 1374	20.	
^{14}Karapiti ^{R}	Taupo	Dates for Papanetu Tephra also date eruption of Karapiti Lapilli[20].		10,11,12,14, 20,21.	Tsg 23-25.
Waiohau ^{R}	Okataina (Mt. Tarawera)	11,250 ± 200 11,100 ± 210	568 878	3,8,13,22,24.	Formerly upper part of Rotorua Ash[22].
Rotorua ^{R}	Okataina (probably in vicinity of Lake Tikitapu)	> 12,350 ± 220 < 13,150 ± 300	1187 1186	3,20,22,24.	Formerly lower part of Rotorua rhyolite pumice[22].
Puketarata ^{R}	Maroa (Puketarata Dome)	> 13,150 ± 300 < 13,800 ± 300	1186 1559	3,14,20,23,25.	

Rerewhakaaitu ^{R}	Okataina (Mt. Tarawera)	14,700 ± 200	716	3,8,13,24.	
Okareka ^{R}	Okataina	-	-	16,24,25.	Correlated with 3rd period ash beds [16] and pinkish brown beds [24].
Te Rere ^{R}	Okataina	-	-	16,24,25	as for Okareka.
Oruanui ^{R}	Taupo	20,670 ± 300 20,000 ± 500 20,500 ± 430 19,850 ± 310	12 330 520 1056	13,16,24 25, 26,27.	Correlated with 2nd period ash beds [16], with pinkish brown beds [24], with Scinde Island volcanic deposits [26], and Aokautere Ash [27]. Pumice breccia member is correlated with Wairakei Breccia Formation [25].
"Yellow-Grey" ^{R}	?Taupo	-	-	28.	Formerly lowermost part of the Oruanui Formation.
***Mangaone Lapilli	Okataina			13,16,24,25,29.	Correlated with 2nd period ash beds [16], with yellow and block beds [24], and beds b and c [29] (beds b and c probably correlate with older dacitic members). At least six members are now recognised.
member e ^{R}		-	-		
member d ^{R}		?27,900 ± 850	876		
member c ^{R}		30,100 ± 1,300 >27,900 ± 1,200 slightly less than <29,700 ± 1,500	868 1147 1136		
member b_2 ^{D}		-	-		
member b_1 ^{D}		-	-		
member a ^{D}		-	-		
Earthquake Flat Breccia ^{R} (Rifle Range Ash)	Okataina (from Earthquake Flat area).	Dates for underlying Rotoiti Breccia also date eruption of this tephra [30].	-	30,31.	
Rotoiti Breccia ^{R} (Rotoehu Ash)	Okataina	>41,000 (at 67% probability) 44,200 ± 4,300 (at 67% probability) 41,700 ± 3,500	643 877 1126	13,16,25,29, 31,32.	Correlated with 2nd period ash beds [16], with grey-banded bed [24], bed d and Rotoiti Breccia [29].
Matahi member ^{B}	Okataina	Dates for Rotoiti Breccia also dates eruption of this tephra.	-	34.	

* For key to - reference to name and age of tephras, <u>see</u> caption on previous page.

** Composition of tephra: R = rhyolite, P = pantellerite, D = dacite, A = andesite, B = basalt.

***Spelt Mangaoni in the original description by Vucetich and Pullar (1969). The formation was named after Mangaoni Siding, a cartographical error for Mangaone Siding on Lands and Survey Map NZMS 1, N77 (Tarawera). The name will appear corrected on future maps. Mangaone is Maori for branch of a stream or watercourse.

The reliable identification of a particular tephra at a stratigraphic section requires that the bed be recognisably different either visually (e.g. black Tarawera scoria, Kaharoa Ash "sugary" white due to high proportion of quartz or Rotoma Ash with darkened paleosol), mineralogically or chemically from others and that any differences be established by adequate investigation of all tephras involved and if possible of the corresponding erupted materials at the source volcanoes (e.g. Ruawahia Dome at Mt. Tarawera, extruded during the same eruptive episode as Kaharoa Ash, Cole 1970a).

FERROMAGNESIAN MINERALOGY

Almost all the acid volcanic rocks of the Taupo Volcanic Zone are porphyritic and contain phenocrysts of plagioclase, hypersthene, titanomagnetite and ilmenite (all normally present), quartz (frequent), calcic-hornblende and biotite (less common), sanidine, augite and cummingtonite (both rare). The predominant constituent of all the tephras studied is glass, which may be in the form of bubble wall fragments, curved, flat or Y-shaped (usually ranging in refractive index from 1.496-1.502) or as pumiceous lumps (ranging in refractive index if fresh from 1.500-1.505 or upto 1.508 if moderately weathered). Phenocrysts and lithic fragments do not often exceed more than 35% of the volume of the tephra deposits studied.

It is well known that variations in abundance and size of the constituents of a particular tephra occur from place to place (especially downwind from source), however there is rarely any primary constituent totally lacking in a sample. Thus a qualitative approach has been attempted in using the dominant ferromagnesian assemblage present as an aid in tephra identification.

Five ferromagnesian assemblages are recognised in the acidic volcanic rocks of the Taupo Volcanic Zone (Ewart 1971a), namely; (a) hypersthene; (b) hypersthene + augite; (c) hypersthene + calcic-hornblende; (d) hypersthene + cummingtonite; (e) biotite + calcic-hornblende ± hypersthene. It has been shown by Ewart (1967a) that these assemblages are significantly correlated with both the total phenocryst content and the modal plagioclase/quartz ratios of the rocks in which they occur. Groups (a) and (b) are typically low quartz or quartz free, with low crystal contents. Group (e) typically has relatively high crystal contents and low plagioclase/quartz ratios. Groups (c) and (d) tend to be intermediate in crystal content but the data for plagioclase/quartz ratios is strongly bimodal (due to a number of quartz free rhyolites in these groups). According to Ewart (1967a) temperature is the dominant factor controlling the ferromagnesian assemblages. However, the bimodal distribution of the plagioclase/quartz ratios of groups (c) and (d) indicate an important additional factor controlling amphibole crystallisation, presumably water pressure and perhaps composition of crystallising liquid.

Optical and chemical properties of minerals have been described by Ewart (1963, 1965a, 1966, 1967b, 1968, 1969, 1971a), Ewart and Taylor (1969) and Cole (1970b). Petrographic (Ewart 1968) and chemical (Ewart 1969) evidence indicate that most phenocrysts crystallised in the magmas in which they are found, and therefore are not xenocrysts.

During the separation (by means of a Frantz Isodynamic Separator) of ferromagnesian minerals (2-4 phi in size) from tephras studied it has been found that there is a gradation between groups (a) and (b), and (c) and (d), thus in Table 3, the number of ferromagnesian assemblages has been reduced to three. The ferromagnesian assemblages assigned to tephras are termed dominant, because small amounts of other ferromagnesian minerals may be present, e.g., Mangaone Lapilli members (a), (b_1) and (b_2) belonging to the hypersthene + augite assemblage may contain < 2%* calcic-hornblende. Results presented in Table 3 are based on the examination of at least two, commonly six, and upto 15 tephra samples from any one formation (sampled both vertically at one locality and also over a wide area).

In the tephras studied, hypersthene is commonly the dominant ferromagnesian mineral present, making it of little use in identification studies. The most useful ferromagnesian minerals are biotite (where it comprises >15% of ferromagnesian phenocrysts present) and the presence of abundant amphibole, as in the case of Rotoehu Ash (abundant cummingtonite with minor amounts of calcic-hornblende) and, Whakatane and Rotoma Ashes (abundant calcic-hornblende with lesser amounts of cummingtonite). Cummingtonite (with $Y \wedge C = 17^{\circ}$ and $2V_{\alpha} = 80\text{-}85^{\circ}$) has only been observed in abundance (upto 90%) in in Rotoehu Ash, in moderate (upto 35%) amounts in Whakatane and Rotoma Ashes and in minor (<5%) amounts in Kaharoa, Waiohau, Rerewhakaaitu Tephras, Te Rere Ash and Mangaone Lapilli members (c), (d) and (e). The presence of cumming-

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* in this section amounts refer to percentage of ferromagnesian assemblage.

DOMINANT PHENOCRYSTIC FERROMAGNESIAN ASSEMBLAGE	TEPHRA
HYPERSTHENE ± AUGITE	Loisels Pumice
	Taupo Pumice Formation
	Mapara
	Whakaipo
	Waimihia
	Hinemaiaia (traces hornblende)
	Opepe
	Poronui
	Karapiti
	Papanetu
	Rerewhakaaitu - phenocryst-poor pumice
	Mangaone Lapilli member (b_2)*
	" " " (b_1)*
	" " " (a)*
HYPERSTHENE (usually dominant unless otherwise indicated) + CALCIC-HORNBLENDE ± CUMMINGTONITE	Rotokawau (traces augite)
	Whangamata
	Whakatane**
	Mamaku (rare biotite)
	Rotoma**
	Waiohau
	Rotorua (may contain considerable amounts of biotite + augite in upper parts)
	Te Rere (traces biotite + augite)
	Oruanui (traces augite + rare biotite)
	Mangaone Lapilli member (e)***
	" " " (d)***
	" " " (c)***
	Rotoiti Breccia (Rotoehu Ash)****
BIOTITE + CALCIC-HORNBLENDE ± HYPERSTHENE	Kaharoa
	Puketarata
	Rerewhakaaitu - phenocryst-rich pumice
	Okareka
	Earthquake Flat Breccia (Rifle Range Ash)

* Traces of calcic-hornblende and rare biotite. Paleosols may contain abundant calcic-hornblende.

** Amphibole (dominantly calcic-hornblende) usually much greater than hypersthene.

*** Traces augite and rare cummingtonite and biotite.

**** Amphibole almost entirely cummingtonite.

Table 3. - Dominant ferromagnesian assemblage of < c. 44,000 yr B.P. acidic tephras erupted from central volcanic region, North Island, New Zealand.

N.B. Aokautere Ash and "Yellow-Grey Tephra" contain same dominant ferromagnesian assemblage as Oruanui Tephra.

tonite in tephras erupted from the Taupo Volcanic Zone is therefore indicative of a source from the Okataina Volcanic Centre.

The Whakatane and Rotoma Ashes usually contain amphibole in greater abundance than hypersthene, but in samples taken from the upper parts, hypersthene approaches or exceeds the amphibole content. This finding is analogous to the occurrence of the most abundant augite in certain pumice members of the Taupo Subgroup (= tephras erupted from Lake Taupo Volcanic Centre over the past c. 9,800 yrs B.P.) which mark the end of eruptive sequences (Ewart 1963). These changes in relative amounts of ferromagnesian phenocrysts are interpreted as showing that the last material ejected was derived from deeper seated magma, with higher temperature and lower volatile content than the earlier ejected magma.

Vertical changes in ferromagnesian assemblage within blocks and lapilli at any one locality are not common. The upper part of Rotoehu Ash may contain small amounts of biotite (see Nairn and Kohn, p.94), and the upper parts of Rotorua Ash may contain upto 20% biotite and 10% augite. Examination of the ferromagnesian mineralogy of the upper parts (within the paleosol) of Mangaone Lapilli members (a), (b_1) and (b_2) show that they may contain upto 50% calcic-hornblende. Since coarser material (pumice blocks and lapilli) sampled from the middle and basal parts of these Mangaone units contain mainly hypersthene + augite with 0-5% calcic-hornblende, it is probable that the paleosols, which represent intervals of weathering between deposition of tephras, are contaminated (perhaps by ? tephric loess). Ferromagnesian mineralogy of 11, near source, samples of Kaharoa Tephra (Cole 1970a) show that this tephra often contains upto 25% olivine and augite in the upper and middle parts of sections, this contamination is attributed to basaltic xenoliths within the pumice and the overlying basaltic Tarawera scoria and ash. Where tephras are contaminated by enclosing tephras of differing composition the use of ferromagnesian assemblages for identification maybe severely limited. This problem may still be overcome; for example, the presence of abundant biotite in thin rhyolite tephras (indicating a source other than Lake Taupo Volcanic Centre;

Taupo Subgroup tephras contain no biotite or hornblende) enclosed by andesitic tephras (containing no biotite) in Tongariro National Park, used in conjunction with sieving of rhyolites (separates larger near source andesitic phenocrysts from finer grained rhyolitic phenocrysts) and general stratigraphic position allows correlations to be made (see Appendix III, p.232). Many ferromagnesian phenocrysts carry glass mantles and these serve to distinguish them from the often present detrital material, which in coastal sections for example although being of volcanic origin are commonly smooth and rounded (the glass having been "worn off"). Glassy selvages are not present in highly altered ashes, (e.g. older andesitic ashes of Taranaki c.> 70,000 yrs B.P.) and in these cases the ferromagnesian minerals themselves maybe corroded to varying degrees, (see Appendix IV, p.266). This degree of weathering of phenocrysts, however, has not been observed in the acidic tephras under study. Further examples of contamination problems are described under the section on titanomagnetite chemistry and its uses for tephra identification (p.115).

Rerewhakaaitu Tephra comprises a phenocryst-poor pumice (hypersthene assemblage) and a phenocryst-rich pumice (biotite + hornblende + hypersthene), the volumes of which are approximately equal (Cole 1970a, c). The phenocryst-rich pumice contains 8-10 times the amount of ferromagnesian phenocrysts found in the phenocryst-poor pumice, thus the ferromagnesian assemblage assigned to bulk samples is biotite + hornblende + hypersthene. This assemblage has been noted in bulk Rerewhakaaitu Tephra samples taken near source (Cole 1970a) and at localities 56 km (Palmer Rd, N94/542499)* and 145 km from source (Mangetepopo Valley, N112/089823). The phenocryst-poor tephra is thought to be primary, but it is uncertain how much of the phenocryst-rich tephra is primary and how much was derived from the existing phenocryst-rich dome through which it probably erupted (Cole 1970d).

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* All grid references in this thesis are based on the national thousand-yard grid of the 1:63,360 topographic map series (NZMS 1).

CHEMISTRY

Chemical composition is one of the most widely used means of identifying tephra. As with ferromagnesian minerals a number of factors must be kept in mind in selection of samples and interpretation of data.

Bulk Chemistry

Chemical analyses of bulk samples are generally of little help for correlation purposes because, as previously stated, the kind and amount of primary minerals and detrital contaminants vary within a given deposit (both vertically and laterally). For example, Lerbekmo and Campbell (1969) studying a Canadian tephra deposit showed that increase in K_2O and SiO_2 and decrease in Na_2O, CaO, MgO and Al_2O_3 with distance from source is a reflection of the increase in glass relative to crystal components. This being due to the lesser density of the glass coupled with its capacity to occur in the fullest range of particle sizes. Element ratios are of little use because of the non-linear way in which most elements vary downwind from source. However, Ca/Sr ratios were found to remain constant despite the change in proportion of Ca-bearing minerals downwind.

A number of chemical analyses of pumice lapilli and blocks, or ash size samples were carried out for most of the important widespread New Zealand tephras. The analyses were carried out not so much for correlation purposes as to detect major chemical differences in coarse near source, relatively unweathered deposits. The analyses also enabled a study of weathering of tephra deposits to see if with similar size grade, site and environmental conditions the degree of weathering of tephra within paleosols could be quantified in terms of time.

According to Lipman (1967) silica-variation diagrams for bulk pumices and coexisting glasses generally show near linear trends, although glasses show lower TiO_2 and total iron than bulk pumices of similar SiO_2 content, probably reflecting the numerous phenocrysts of titanomagnetite. The rapid chemical analysis of fresh pumice blocks and lapilli is therefore a quick way of showing major chemical differences that may exist between tephras and indicates to what extent future work on individual constituents of tephra (e.g. glass) may be profitable.

Bulk chemical analyses of some of the tephras being studied have been reported by Berry 1928 (chalazoidites from Oruanui Tephra), Grange 1929 (?Mamaku Ash and Taupo Pumice, plus numerous weathered tephras in present day soils or within 50 cm of the surface), Grange 1931 (present day soil forming and older tephras - mostly all weathered), Grange 1937 (Tarawera scoria and Earthquake Flat Breccia pumice), Ewart 1963 (glass from selected Taupo Subgroup Tephras), Cole 1966 (Tarawera Basalt, Kaharoa, Waiohau and Rerewhakaaitu Ashes) and Ewart 1969 (Puketarata Dome, erupted during the same eruptive episode as Puketarata Ash - Lloyd 1972).

Results of bulk chemical analyses of fresh and weathered tephras, analysed by X-ray fluorescence (X.R.F.) or atomic absorption spectrophotometry (A.A.) or both (see Appendix I for analytical procedures) are given in Table 4. With the exception of some values of K_2O, CaO and total iron, for similar samples elemental values determined by X.R.F. and A.A. are generally in broad agreement.

Analyses show that relatively fresh pumice samples of Kaharoa (11841, 11842), Whakatane (11850, 11851), Mamaku (11854), Rotoma (11855, 11856), Waiohau (11860, 11861) and Rerewhakaaitu (11870, 11871, 11872) Ashes, all erupted from the Okataina Volcanic Centre, contain similar amounts of major elements (TiO_2 was not analysed by A.A., but values given by Cole 1966 range between 0.11-0.26%, averaging 0.21%). These tephras are less "basic" than Rotorua Ash (11864) which contains less SiO_2 and K_2O and more total iron, MgO, CaO and TiO_2, with slightly higher MnO. Taupo Subgroup tephras (Grange 1929, analysis T 3968/2 and glasses from selected phenocryst poor Taupo pumices, Ewart 1963) are also more "basic", and can be distinguished from Rotorua Ash by their higher total iron and MnO contents, and lower MgO and slightly lower TiO_2 contents. Puketarata Dome (P29115, Ewart 1969) contains higher SiO_2 and MgO than Taupo Subgroup beds and more

Table 4. - Major element analyses of some fresh and weathered < c. 44,000 yr B.P. acidic tephras erupted from the Taupo Volcanic Zone. Analyses were carried out by atomic absorption spectrophotometry (unless otherwise indicated). Details of all sample localities are given in Appendix II.

List of Parker's Indices (P.I.s). [see p. 129].

11841 = 67.2, 11842 = 71, 11851 = 67.2,
11860 = 64.9, 11862 = 56.8, 11863 = 43.3
11864 = 66.7, P28362 = 70.8, P29115 = 73.7,
11881 = 58.2, 11882 = 46.0, 11883 = 52.9,
11884 = 42.7, 11885 = 64.1, 11886 = 63.9.
11887 = 64.0, 11888 = 65.1, 11889 = 66.0,
11890 = 69.1, 11891 = 60.3, 11892 = 66.2,
11893 = 66.4, 11894 = 56.3, 11895 = 60.2,
11896 = 51.4, 11897 = 58.9, 11898 = 56.1,
11899 = 56.0, 11900 = 48.7, 11901 = 61.2,
11902 = 64.2, 11903 = 45.3, 11904 = 63.2,
11905 = 53.8, 11906 = 61.7, 11907 = 52.2,
11908 = 48.5, 11909 = 56.5, 11910 = 47.0,
11911 = 40.6.

average of 25 rhyolite lavas and domes = 70.9.
" " Taupo Pumice deposits = 71.3.
" " 17 rhyolitic ignimbrites = 69.5.
P29177 Dacite (Mt. Maungaongaonga) = 74.3.
P28364 Waiteariki Ignimbrite (glass) = 72.4.
Mt. Tauhara Dacite = 69.7.
P30427 Mangaone Lapilli member (b_2) = 72.5.

V.U.W. SAMPLE No. %	Ka 11841	Ka 11842	WK 11851	wK 11850	Ma 11854	Rai 11855	Rm 11856	Rm 11931	Rm 11932	PK 11867	Wh 11860	Wh 11861	Wh 11862	Wh 11863
SiO$_2$	74.38	74.44	73.40	72.80	73.62	72.16	73.14	69.55	73.00	73.82	73.10	72.53	69.71	59.65
Al$_2$O$_3$	12.85	12.35	12.94	13.79	13.48	13.59	12.73	14.85	13.15	12.76	12.82	13.38	15.94	18.81
*Fe$_2$O$_3$	1.33	1.06	1.07	1.31	1.26	1.52	1.44	1.55	1.48	1.07	1.45	1.94	1.87	3.77
MgO	0.23	0.14	0.16	0.19	0.21	0.26	0.23	0.25	0.25	0.16	0.21	0.24	0.23	0.46
CaO	1.38	0.97	0.92	1.16	1.30	1.32	1.27	1.04	1.12	1.06	1.11	1.16	1.03	0.96
**Na$_2$O	4.15	4.12	3.88	3.97	4.08	3.96	4.25	3.54	3.68	3.88	4.00	3.84	3.44	2.58
K$_2$O	2.92	3.55	3.38	3.13	3.02	2.77	3.06	2.60	2.50	3.18	3.04	3.02	2.58	1.86
TiO$_2$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P$_2$O$_5$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MnO	0.06	0.06	0.06	0.06	0.06	0.08	0.07	0.07	0.06	0.06	0.07	0.07	0.07	0.06
***LOI	2.59	2.94	3.63	3.17	2.28	4.34	3.60	5.90	4.90	3.78	3.43	3.39	4.59	11.17
TOTAL	99.89	99.63	99.44	99.58	99.31	100.00	99.79	99.35	100.14	99.77	99.23	99.57	99.46	99.32

	Rr x11864	11864	Rr x11865	11865	Rr x11866	RK 11866	RK 11868	11869	RK 11870	RK 11871	RK 11872	Ou x11877	Ou x11876	Ou x11878
SiO$_2$	71.44	71.88	69.72	69.98	67.76	67.58	65.49	71.47	73.19	74.11	74.54	70.14	72.60	71.64
Al$_2$O$_3$	13.12	13.70	14.13	14.60	15.76	15.41	16.56	14.32	12.95	12.64	13.08	13.54	14.26	13.43
*Fe$_2$O$_3$	2.17	2.20	2.27	2.17	2.69	2.85	3.31	2.14	1.55	1.24	1.24	3.13	2.42	2.38
MgO	0.47	0.47	0.47	0.48	0.55	0.57	0.41	0.32	0.22	0.18	0.16	0.56	0.36	0.32
CaO	1.89	2.01	1.85	1.97	1.48	1.68	1.31	1.58	1.29	1.19	1.18	1.45	2.22	1.10
**Na$_2$O	4.12		4.05		3.58		3.04	3.61	3.96	4.12	4.08	2.24	2.97	2.31
K$_2$O	2.66	2.74	2.50	2.57	2.28	2.28	2.42	2.44	3.07	3.27	3.21	2.88	2.51	2.21
TiO$_2$	0.33	-	0.34	-	0.35	-	-	-	-	-	-	0.26	0.22	-
P$_2$O$_5$	0.09	-	0.13	-	0.09	-	-	-	-	-	-	0.01	0.03	-
MnO	0.08	-	0.09	0.08	0.08	-	0.08	0.06	0.07	0.07	0.06	0.12	0.10	0.03
***LOI	3.03		3.62		5.50		6.98	3.86	3.02	2.69	2.13	6.16	3.14	6.23
TOTAL	99.40		99.17		100.12		99.60	99.80	99.32	99.51	99.68	100.49	100.83	99.65

V.U.W. SAMPLE No.	Mn(e) x11881	11881	Mn(e) x11882	11882	Mn(e) x11883	11883	x11884	11884	11889	(d) 11885	(d) 11886	(d) 11887	11888	11890	11891
%															
SiO_2	69.30	70.62	62.31	62.50	65.92	66.71	62.80	62.23	71.37	71.33	72.02	72.22	71.20	73.30	71.27
Al_2O_3	15.33	15.07	20.05	20.12	17.54	16.94	19.68	19.28	13.78	13.47	13.76	13.75	13.48	13.24	13.69
*Fe_2O_3	1.96	1.92	3.52	3.53	2.84	2.88	3.65	3.56	1.72	1.62	1.82	1.96	2.03	1.52	1.96
MgO	0.26	0.26	0.34	0.35	0.32	0.31	0.34	0.34	0.27	0.30	0.24	0.27	0.29	0.26	0.30
CaO	1.48	1.33	1.37	1.46	1.15	1.24	1.01	1.08	1.54	1.36	1.33	1.29	1.53	1.26	1.30
**Na_2O	3.65		3.00		3.41		2.55		4.15	4.01	4.04	4.02	4.01	4.40	3.77
K_2O	2.37	2.42	1.62	1.62	2.05	2.05	1.88	1.84	2.72	2.69	2.66	2.69	2.78	2.95	2.53
TiO_2	0.28	-	0.46	-	0.39	-	0.44	-	-	-	-	-	-	-	-
P_2O_5	0.07	-	0.06	-	0.05	-	0.05	-	-	-	-	-	-	-	-
MnO	0.11	-	0.08	0.07	0.09	0.07	0.06	0.06	0.08	0.09	0.11	0.09	0.09	0.10	0.10
***LOI	4.60		6.37		6.00		6.42		4.20	5.17	3.44	3.56	3.98	2.89	4.91
TOTAL	99.41		99.18		99.76		98.88		99.83	100.04	99.42	99.85	99.39	99.92	99.83

	(c) x11892	11892	(c) x11893	11893	(c) x11894	11894	(c) x11895	11895	(c) x11896	(b2) x11897	11897	x11898	11898	(b2) x11900	11900
SiO_2	71.75	72.42	72.43	71.53	67.42	66.95	69.84	70.19	64.79	66.96	67.45	65.55	64.89	61.94	62.26
Al_2O_3	13.32	13.40	13.17	13.29	15.50	14.98	14.59	14.68	17.81	15.50	15.27	16.75	16.48	18.15	17.90
*Fe_2O_3	1.54	1.51	1.55	1.59	2.34	2.37	1.98	1.97	3.46	2.72	2.74	3.49	3.77	3.88	3.93
MgO	0.27	0.27	0.25	0.25	0.33	0.34	0.31	0.29	0.31	0.50	0.49	0.64	0.66	0.72	0.72
CaO	1.18	1.26	1.22	1.33	1.53	1.48	1.27	1.48	1.85	1.83	1.87	2.26	2.24	2.20	2.32
**Na_2O	4.17		4.22		3.68		3.60		3.09	3.73		3.57		2.95	
K_2O	2.71	2.82	2.68	2.71	2.30	2.31	2.56	2.54	1.68	2.13	2.17	1.92	1.85	1.63	1.61
TiO_2	0.21	-	0.23	-	0.34	-	0.29	-	0.44	0.45	-	0.53	-	0.65	-
P_2O_5	0.06	-	0.08	-	0.07	-	0.05	-	0.11	0.07	-	0.09	-	0.16	-
MnO	0.09	0.09	0.10	0.09	0.09	0.09	0.09	0.07	0.14	0.09	0.09	0.12	0.11	0.11	0.10
***LOI	3.93		3.80		5.58		5.24		5.77	5.11		4.54		6.55	
TOTAL	99.23		99.73		99.18		99.82		99.45	99.09		99.46		98.94	

V.U.W. SAMPLE No. %	(b2) ^{x}11899	11899	11902	(b1) 11901	(b1) ^{x}11903	(a) 11907	(a) 11905	(a) 11906	(a) ^{x}11904	11904	(Rb) ^{x}11910	Re ^{x}11909	Re 11909	^{x}11908	Re 11911
SiO_2	66.10	66.95	67.48	66.90	64.29	66.07	65.55	66.53	64.60	65.40	66.53	69.78	70.14	70.97	61.79
Al_2O_3	15.70	15.42	15.09	15.03	16.58	17.21	16.83	16.38	16.99	15.61	17.23	16.02	15.27	14.50	21.62
*Fe_2O_3	3.31	3.29	3.53	4.29	4.38	3.83	4.17	3.05	3.79	3.26	3.27	2.19	2.28	3.00	2.80
MgO	0.61	0.62	0.97	0.91	1.07	0.68	0.49	0.68	0.93	0.86	0.47	0.36	0.34	0.68	0.56
CaO	2.35	2.26	2.76	2.90	2.92	2.13	2.53	2.56	2.60	2.67	1.21	1.29	1.36	2.63	1.88
**Na_2O	3.38		4.05	3.85	3.01	3.03	3.27	3.67	3.69		2.91	3.22		2.97	2.87
K_2O	2.09	2.09	2.03	1.86	1.35	2.01	1.89	2.34	1.75	2.09	2.29	2.63	2.60	1.52	0.98
TiO_2	0.52		-	-	0.76	-	-	-	0.63	-	0.41	0.28	-	0.56	-
P_2O_5	0.14		-	-	0.11	-	-	-	0.07	-	0.08	0.05	-	0.05	-
MnO	0.11	0.10	0.12	0.12	0.12	0.16	0.16	0.08	0.11	0.12	0.08	0.09	0.10	0.14	0.06
***LOI	5.42		3.09	4.74	5.29	4.62	4.67	3.93	5.44		5.03	4.15		2.83	6.67
TOTAL	99.73		99.12	100.60	99.88	99.74	99.56	99.22	100.60		99.51	100.06		99.85	99.23

* Total Fe as Fe_2O_3

** Na_2O was analysed by atomic absorption spectrophotometry

*** Loss on ignition between 110° - 1000°C

x = Sample analysed by X-ray fluorescence

\- not determined.

SiO_2 and K_2O and slightly less TiO_2 than Rotorua Ash.

Rotorua Ash has similar contents of SiO_2 and total iron, but higher Na_2O and MgO, and slightly less CaO than Oruanui Ash (11876) which is in turn more "basic" than Mangaone Lapilli Formation members (e) (11889), (d) (11886, 11887) and (c) (11890, 11892, 11893) which are similar in chemical composition to the younger Okataina Volcanic Centre tephras (excluding Rotorua Ash). The older Mangaone Lapilli Formation members (b_2) (11899), (b_1) (11902) and (a) (11905, 11906) are dacitic in composition. Rotoehu Ash (11908) is slightly more "basic" than Rotorua Ash which is approximately similar in composition to Earthquake Flat Breccia pumice (Grange 1937, Analysis No. 3 P17485).

The major element compositions of pumice blocks and lapilli therefore indicate that even though most are rhyolitic in composition, they show differences which are likely to be reflected in the chemistry of individual constituents.

Chemistry of Glass and Phenocrysts

If one constituent is common to all tephras, and can be easily concentrated, then its chemistry can be compared between samples of the same tephra and between different tephras. Glass, plagioclase, hypersthene, ilmenite and titanomagnetite are common to all tephras being studied and are therefore the potentially most useful constituents for tephra identification studies.

Glass

Glass chemistry as a distinguishing criterion is preferred by most North American workers. However, the literature is not always clear as to whether analyses reported are for pumice or glass only, or both with varying amounts of phenocryst inclusions. In this respect the technique of Smith and Westgate (1969) deserves special comment since their data were obtained by use of an electron probe. The merit of this approach is the degree of control, which allows, phenocrysts, microlites and bubbles to be avoided during analysis. An apparent limitation of major element analysis however is the influence of weathering, particularly in older samples.

Chemical analyses of glasses, mainly for minor and trace elements, from central North Island acidic tephras have been reported by Ewart et al(1968a)(Taupo Pumice, Waimihia Lapilli, Puketarata Dome, plus numerous domes from Okataina Volcanic Centre which are considered to be co-magmatic with many tephras erupted from that centre, i.e. Kaharoa, Whakatane, Mamaku, Rotoma, Waiohau, Rerewhakaaitu and the three younger Mangaone Lapilli members), and McCraw and Whitton (1971) (Whangamata Ash, Taupo Pumice and Rotorua Ash). Previously published major element glass analyses from six of the tephras being studied, together with partial glass analyses of three further tephras are presented in Table 5.

McCraw and Whitton (1971) showed that the chemistry of Whangamata Ash was similar to that of Mayor Island volcanic rocks and different from Taupo Lapilli and Rotorua Ash and andesitic tephra erupted from Tongariro and Egmont volcanoes. Ewart et al (1968b) have also shown that the average Mayor Island pantellerite is markedly different in composition than the average Taupo Volcanic Zone rhyolite. The absolute values of similar rocks and tephras analysed by Ewart et al (1968a,b) and McCraw and Whitton (1971) generally differ, but the trends indicated by the compositions are comparable. Whangamata Ash (and Mayor Island pantellerite) when compared with all Taupo Volcanic Zone acidic rocks is markedly enriched in Mn, Ga, Mo, Zr, Ti, Li, Cs, Be, Rb, total Rare Earth Elements and highly charged cations, and depleted in Ba, Sr, Mg, Ca, Sc, V and Cr, and is therefore chemically distinctive. Taupo Pumice and Waimihia Lapilli when compared with Okataina Volcanic Centre glasses contain markedly higher Ti, Mn, Sc, Zr, Mg, Sr and total iron, slightly higher Ca and Na, and lower Rb, Ba, K and Si. Glass from Puketarata Dome (Maroa Volcanic Centre) contains similar K, Rb, Ca and total iron to glass from Okataina Volcanic Centre eruptives but differs in containing lower Sc, Zr, Mg, Sr, Na and Al, and Ba values intermediate between those of glasses from Taupo and Okataina Volcanic Centres. Within Okataina Volcanic Centre, cummingtonite-bearing rhyolites (P28360 and P27580, the latter

SAMPLE NO.	1	2	3	4	5	6	7	8	9
%									
SiO_2	71.2	70.5	71.3	74.8				74.1	68.5
Al_2O_3	13.2	12.6	12.9	12.1				11.8	13.4
Fe_2O_3	0.75	0.55	0.65	0.2				0.49	0.8
FeO	1.35	1.35	1.25	0.8				0.70	1.6
MgO	0.30	0.25	0.15	<0.1				0.05	0.8
CaO	1.35	1.20	1.25	0.8	0.82	1.08	1.54	0.95	1.9
Na_2O	4.75	4.65	4.30	4.3	4.10	3.90	3.84	3.95	4.8
K_2O	2.85	2.90	3.10	3.4	4.12	3.60	4.00	4.10	2.5
TiO_2	0.25	0.25	0.15	0.24				0.03	0.56
P_2O_5	0.04	0.05	0.05	0.01				0.13	0.10
MnO	0.10	0.10	0.15	0.07				0.05	0.09
H_2O^+	2.63	3.47	3.92	2.8				3.00	5.0
H_2O^-	0.74	0.46	0.48	0.2					0.2
TOTAL	99.51	98.33	99.65	99.82				99.35	100.25

KEY

1 Taupo Lapilli (Tsg 3) [Ewart 1963].
2 Waimihia Lapilli (Tsg 15) [Ewart 1963].
3 Karapiti Lapilli (Tsg 25) [" "].
4 Rotoma Ash P30392 [Ewart and Healy 1965a].
5 Kaharoa Ash 11061/7 [Cole 1966].
6 Waiohau Ash 11170 [" "].
7 Rerewhakaaitu Ash 11171 [Cole 1966].
8 Puketarata Dome P29115 [Ewart 1969].
9 Mangaone Lapilli member ?(b_2) P30427 [Ewart and Healy 1965a].

Table 5. - Major element analyses of glass from acidic tephras.

also contains calcic-hornblende) contains less Mg and to a lesser extent Ca, Fe and V than calcic-hornblende-bearing rhyolites.

Using a semi-quantitative optical emission spectrographic method the author compared glass chemistry from Oruanui Ash, Taupo Pumice and Kaharoa Ash. Taupo Pumice and Kaharoa Ash, showed relative differences previously described. Oruanui Ash glass showed lower Mn, Ti, Ba, Mg, Sr, Ca and Zr values when compared with Taupo Pumice, and higher Mg and Ca, slightly higher Ti and Zr, and lower Ba when compared with Kaharoa glass.

Glass chemistry therefore shows differences between Whangamata Ash and acidic Taupo Volcanic Zone tephras, and differences between Taupo Subgroup tephras, most Okataina Volcanic Centre eruptives, Oruanui Ash and Puketarata eruptives. Although work on glass chemistry of Taupo Volcanic Zone tephras may be considered minimal, results to date show differences generally similar to trends previously determined for whole rock chemistry. Limited data therefore show the potential usefulness of glass chemistry in N.Z. for tephra identification.

Plagioclase

Because of, compositional variations in individual phenocrysts due to complex oscillatory zoning which significantly affect refractive indices,and problems of rapidly obtaining a relatively pure sample (Ewart and Taylor 1969, Ewart 1969), plagioclase is considered unsuitable for rapid tephra identification. Despite these problems, plagioclase compositions show a correlation with coexisting residual glass and the type of ferromagnesian assemblage (Ewart 1969). Bulk plagioclase compositions (Ewart and Taylor 1969) show that hypersthene-bearing Taupo Subgroup tephras contain higher Mg, Ca and total iron, and less Na and Ba contents than plagioclases from calcic-hornblende + hypersthene-bearing Okataina Volcanic Centre eruptives. Biotite-bearing Puketarata Dome contains more Na, K, Ba and Rb, and less Ca, Sr and total iron contents than plagioclases from either Taupo or Okataina Volcanic Centres, and less Mg than Taupo Volcanic Centre plagioclases. Within the Okataina Volcanic Centre rocks, cummingtonite-bearing rhyolite (P28360 and P27580) contains higher Na, K and Ba, and less Ca, Sr, Mg and total iron than calcic-hornblende rhyolites.

Hypersthene

Analyses of hypersthenes from Mangaone Lapilli member (?b), Taupo Subgroup tephras and Okataina Volcanic Centre eruptives have been published by Ewart (1967b, 1971a) and Ewart and Taylor (1969). Within Taupo Subgroup tephras Fe^{3+}, Ti and Mg decrease, and Fe^{2+} and Mn increase from oldest to youngest members (Ewart 1967b, 1971a). Mangaone member (?b) has higher Ca, Mg and Al, and lower Mn values than either Taupo Volcanic Centre or Okataina Volcanic Centre rhyolitic eruptives. Taupo Subgroup tephras have higher Ca, Sc and Ni, and ~~less~~ lower Mn values than rhyolitic eruptives from Okataina Volcanic Centre.

The refractive index α_{min} for hypersthenes of Taupo Subgroup tephras (Ewart 1967b) is higher than those from rhyolites of Tarawera Volcanic Complex in Okataina Volcanic Centre (Cole 1970b). No exsolution structures have been noted optically in the hypersthenes and zoning appears to be uncommon (Ewart 1967b). Small exsolution structures of clinopyroxene have, however, been observed (by electron probe) in hypersthene grains from Waimihia Lapilli (Fig 2). More work to assess the amount and nature of the exsolution structures and chemistry of their host crystals will have to be carried out before the petrological significance of these grains can be interpreted.

Augite

A major element analysis of augite from Mangaone member (?b) is given by Ewart (1971a). An augite analysis from Taupo Subgroup member 19 (Ewart 1967b) is regarded as being andesitic contamination (see p. 115) and this conclusion is borne out by its similar chemistry to andesitic augites (Ewart 1971a). Augite from the dacitic Mangaone member (?b) contains significantly higher amounts of Mn than is found in andesitic augites.

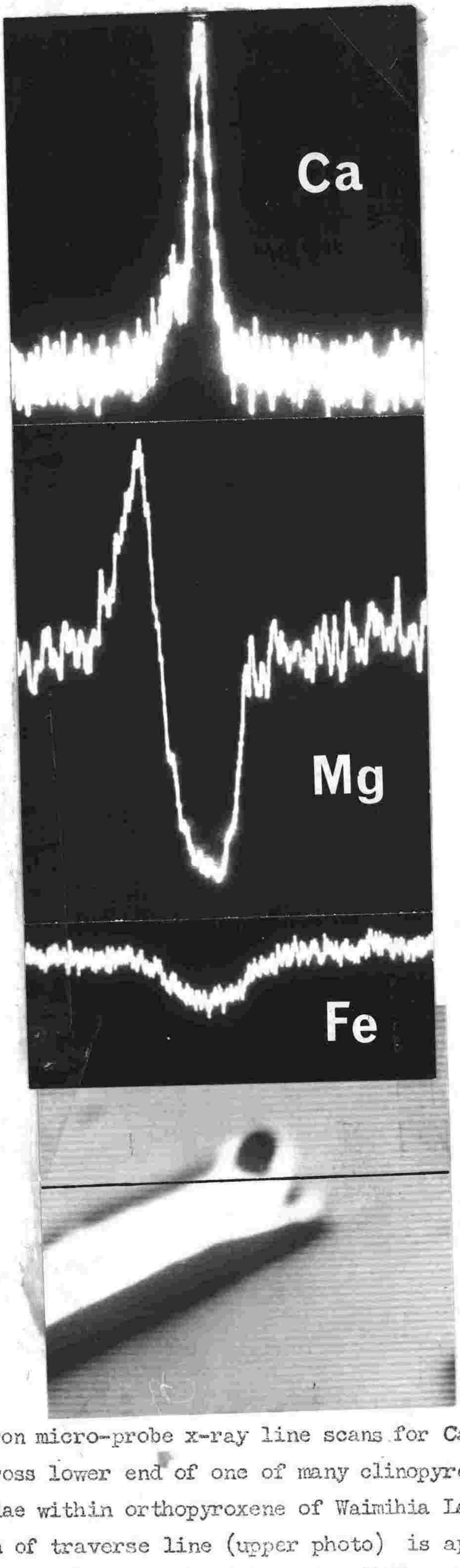

Fig. 2. - Electron micro-probe x-ray line scans for Ca, Mg and Fe across lower end of one of many clinopyroxene lamellae within orthopyroxene of Waimihia Lapilli (11847). Length of traverse line (upper photo) is approximately 40 microns. Photographs taken at x 1400 magnifications.

Amphibole

Calcic-hornblende analyses are given by Ewart and Taylor (1969) and Ewart (1971a). Analyses show that Puketarata Dome contains more total iron, Cr, Ni, Co, La, Ba and K, and less Mg, Sc, Ti, Sr and generally less Ca than calcic hornblendes from Okataina Volcanic Centre eruptives.

Major element analyses of cummingtonite have been reported by Ewart *et al* (1971).

The optic sign of cummingtonite appears to be variable. In the tephras studied it is always -ve and this finding is in agreement with the findings of Cole (1970b) for cummingtonite in rhyolites of the Tarawera Volcanic Complex. Cummingtonites described by Kuno (1938, 1950) from dacite eruptives of Hakone Volcano, Japan and Nasmith *et al* (1967) from St. Helens Y ash in North America have a +ve optical sign.

Biotite

Two major element analyses reported by Ewart (1971a) show that Puketarata Dome biotite contains more Ca and total iron, and less Si, Al, Na and Mg than biotite from an Okataina Volcanic Centre lava.

Iron-Titanium Oxides

Bulk, titanomagnetite analyses of some Taupo Subgroup members have been reported by Ewart (1967b). The Karapiti Lapilli (mem. 25) typically shows lower Mn and Mg abundances than younger members, and titanomagnetite from member 19 has higher Mg and total iron, and lower Ti and Mn than any other Taupo Subgroup member (*see* p. 221).

Electron microprobe analyses of coexisting titanomagnetites and ilmenites from Rotoiti Breccia Formation, Rotoma Ash and rhyolite domes within Okataina Volcanic Centre, and four Taupo Subgroup tephras have been reported by Ewart *et al* 1971. Titanomagnetite of tephras erupted from Okataina Volcanic

Centre have slightly higher total iron and slightly lower Ti contents than domes, with V contents varying between samples. By contrast, all ilmenites are similar in composition. The general similarity of tephra and 'dome' iron-titanium oxide chemistry from Okataina Volcanic Centre eruptives again shows the general similar chemistry of many magmas erupted from this centre. Cummingtonite-bearing rhyolites in Okataina Volcanic Centre (P30411, P30407 - Rotoiti Breccia Formation and P28360 - rhyolite dome) show generally similar titanomagnetite compositions to calcic-hornblende rhyolites although P28360 contains lower Mg. Titanomagnetites of Taupo Subgroup when compared with Okataina Volcanic Centre eruptives contain higher Ti and Al, and lower V and total iron; and ilmenites higher Ti and lower Mn.

IDENTIFICATION OF NEW ZEALAND TEPHRA-LAYERS BY EMISSION SPECTROGRAPHIC ANALYSIS OF THEIR TITANOMAGNETITES

B. P. KOHN

Kohn, B.P. 1970: Identification of New Zealand tephra-layers by emission spectrographic analysis of their titanomagnetites. *Lithos 3*, 361–368.

Tephra-layers are used for correlating Late Quaternary deposits in the North Island of New Zealand. A quick chemical method of tephra identification that can be used as a check for field correlations is described.

Titanomagnetite, being found in all the tephra-deposits studied, being resistant to weathering, and being easily extracted, was spectrographically analysed. Seventy-one samples of titanomagnetite from fifteen widespread tephra-layers ranging in age from 84–41,000 years B.P. were analysed for Ti, Mg, Mn, Ca, V, Cr, Co, Ni, Zr and Cu using an optical emission spectrographic technique. It was found that the ratios of Ti/V, V/Mn and Co/Mn used in combination, served to identify each of the tephra-layers.

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The value of tephra (volcanic ash) layers as stratigraphic markers in solving problems in Quaternary geology, paleopedology and archaeology is widely recognised (Thorarinsson 1944, 1949, Wellman 1962, Healy et al. 1964, Powers & Wilcox 1964, Fryxell 1965, Wilcox 1965, Ruxton 1966, Pullar 1967, Momose et al. 1968, Ninkovich 1968, Pullar & Warren 1968, Vucetich 1968, Vucetich & Pullar 1969). The advantages and disadvantages of various field and laboratory techniques for correlation have been recently reviewed by Wilcox (1965) and Smith & Westgate (1969).

In the field, stratigraphic position, thickness, and general appearance enable tephra-layers to be identified in some sections, but in most sections there are one more tephra-layers that cannot be identified with certainty.

Laboratory studies have included: (1) The determination of the ranges and modal values of the refractive index of volcanic glass (Ewart 1963, Wilcox 1965 and Steen & Fryxell 1965). (2) The phenocryst assemblage and properties of the individual phenocrysts (Ewart 1963, 1966, Powers & Wilcox 1964, Wilcox 1965, Nasmith et al. 1967, Westgate & Dreimanis 1967, Cole 1969). (3) The major and trace element composition of ash, pumice or volcanic glass (Ewart 1963, Czamanske & Porter 1965, Wilcox 1965, Theisen et al. 1968, Smith & Westgate 1969). (4) The thermomagnetic properties of the ferromagnetic minerals (Ewart 1967, Momose et al. 1968). (5) The radiocarbon dating of organic matter associated with a tephra-layer.

Although determination of the refractive index of volcanic glass is a quick

Table 1. The stratigraphic succession and ages of the fifteen Late Quaternary tephras studied. All the tephras are from the North Island of New Zealand

Tephra	*Radiocarbon age* (years before 1960)	*Stratigraphically inferred ages* (not radiocarbon dated)	*Reference to age*
Tarawera		Historic eruption in 1886	
Kaharoa	930 ± 70		Vucetich & Pullar (1964)
Loisels pumice		1,260	Wellman (1962)
Taupo lapilli	1,829 ± 17		Healy (1964)
Waimihia	3,440 ± 50		Healy (1964)
Rotokawau			
Whakatane	5,180 ± 80		Pullar (pers. comm. 1970)
Mamaku		8,000	Pullar (pers. comm. 1969)
Rotoma		9,000	Pullar (pers. comm. 1969)
Waiohau	11,250 ± 250		Cole (1969)
Rotorua		13,000	Pullar (1967)
Rerewhakaaitu	14,700 ± 200		Vucetich & Pullar (1969)
Oruanui	20,500 ± 430		Vucetich & Pullar (1969)
Mangaoni	26,300 ± 700		Vucetich & Pullar (1969)
Rotoehu	41,000 (at 67% probability)		Vucetich & Pullar (1969)

and easy method, it has not been found to be very useful in New Zealand, because of the small range in refractive indices of glasses in most of the major tephra-deposits (Wellman 1962, Ewart 1963, Ninkovich 1968). The phenocryst assemblage of some New Zealand Quaternary tephra-deposits is distinctive near their sources (Ewart 1966, Cole 1969), but is less distinctive away from source (Wellman 1962). The major and trace element chemistry of most widespread New Zealand Quaternary tephra-layers is very similar (Ewart 1963, 1966, Healy et al. 1964, Ewart et al. 1968). The use of the radiocarbon method for dating tephra-layers and the problems arising from this technique have been discussed by Healy, Vucetich & Pullar (1964, pp. 7–8) and Damon (1968).

In the present study, fifteen widespread Quaternary tephra-deposits in the North Island of New Zealand have been identified by the rapid chemical analysis of their titanomagnetite. Titanomagnetite was chosen as a suitable mineral because: (a) It is common in all the volcanic rocks of the central North Island of New Zealand (Ewart 1966). (b) It has been shown to be stable during weathering by Aomine & Wada (1962) and Ruxton (1968). (c) Its range in chemical composition and thermomagnetic properties is considerable as shown by Ewart (1967), Momose, Kobayashi, Minagawa & Machida (1968) and Duncan & Taylor (1968). (d) It is easily extracted by magnet in a reasonably pure form.

The stratigraphic succession and known ages of the tephra-deposits studied are given in Table 1. All tephra-deposits studied were sampled over a large area.

Experimental procedure

Most samples were ground directly in an agate mortar; a few were broken down in a jaw crusher and then ground in a Tungsten Carbide Alloy grinding vessel on a 'Tema' mill. Titanomagnetite was extracted by hand magnet, with the sample and the magnet immersed in acetone. Titanomagnetite concentrates were purified by repeated magnetic separations under acetone, the final concentrates being at least 98 % pure. The titanomagnetites were then mixed with four times their weight of a carbon-palladium mixture, the palladium acting as a spectrographic internal standard. The elements Ti, Mg, Mn, Ca, V, Cr, Co, Ni, Zr and Cu were determined on a Hilger-Littrow spectrograph. Johnson-Matthey 'Specpure' oxides of the elements listed above were mixed in a base of 'Specpure' Fe_2O_3 (9 parts) and TiO_2 (1 part). A set of standards was obtained by successive dilution with the base. Spectrographic operating conditions are shown in Table 2. The lines Ti 3029, Mg 2781, Mn 2939, Ca 3158, V 3102, Cr 2677, Co 3453, Ni 3050, Zr 3273, Cu 3274 and Pd 3027 were read. The analytical precision, expressed as relative deviation, was ± 8%.

Element and internal standard lines were read with a Hilger non-recording microphotometer, the galvanometer deflections being transformed to X-values, where $X = \frac{1}{2}$ (optical density + Seidel density). Working curves were prepared from the standards, using the technique described by Tennant & Fellows (1967) in which plots of $(1/\gamma)$ (X internal std.)/(X element) against log concentration are prepared for each element. Here γ is the plate gamma as calculated from predetermined relative intensities of a set of eight iron lines in a pure spark spectrum.

Because of the complexity of the spectra, a fine grained high contrast plate was desirable for maximum plate resolution. Ilford thin film half tone plates proved good but have the disadvantage of varying plate gamma over the wavelength range used, thus possibly invalidating the calibration method. Hence several standards of suitable concentration were normally exposed on each plate to check for working curve 'drift'. Furthermore, two previously analysed titanomagnetites from andesitic and dacitic lavas from the central

Table 2. Spectrographic apparatus and operating conditions

Spectrograph: Hilger-Littrow quartz and glass (E 478).
Electrodes: Anode – National Carbon Co. AGKSP graphite
4.4 mm o.d. × 3.2 mm i.d. × 5 mm deep.
Cathode – National Carbon Co. SPK carbon sharpened to a 60° cone.
Wavelength range: 2480–3600 Å (quartz optics).
Slit width: 10 microns.
Analytical gap: 4 mm (shielded electrodes).
Exposure time: 10 sec. at 5 amps, then arced to completion at 15 amps.
Photographic emulsion: Ilford Thin Film Half Tone.
Microphotometer: Hilger non-recording (H 451).

Table 3. Average compositions of titanomagnetite from some Late Quaternary tephras in the North Island of New Zealand (values are in parts per million unless otherwise indicated)

Tephra	Ti%	Mg%	Mn%	Ca%	Zr	V	Cr	Co	Ni	Cu	No. sam anal
Tarawera scoria and ash	6.08	1.090	0.557	0.908	287	1247	72	28	75	14	
Kaharoa ash											
northern lobe	5.86	0.483	0.686	0.533	694	1372	49	33	43	27	1
south-eastern lobe	7.13	0.462	0.626	0.361	913	933	18	31	25	41	
Loisels pumice	6.28	1.300	0.468	0.828	36	978	4	103	175	101	
* Taupo Lapilli	13.10	1.070	0.615	0.498	67	638	135	17	27	24	
* Waimihia Formation	14.30	0.751	0.558	0.459	328	720	140	25	33	38	
Rotokawau ash	7.97	0.550	0.570	0.275	304	2061	210	84	72	45	
Whakatane ash	6.13	0.576	0.597	0.280	1003	1190	45	33	31	26	
Mamaku ash	5.34	0.590	0.537	0.312	841	1325	115	48	33	40	
Rotoma ash	5.78	0.591	0.656	0.197	688	1504	47	40	22	41	
Waiohau ash	5.97	0.629	0.537	0.149	813	1710	65	35	27	23	
Rotorua ash	5.75	0.950	0.583	0.338	447	2400	140	51	44	42	
Rerewhakaaitu ash											
phenocryst-rich	5.66	0.362	0.602	0.381	660	1852	148	36	34	28	
phenocryst-poor	4.52	0.562	0.520	0.415	780	1355	50	37	27	38	
Oruanui Formation	7.36	0.723	0.464	0.275	304	2666	274	71	80	41	
Mangaoni Lapilli											
(beds C and E)	5.38	0.789	0.641	0.200	866	859	10	15	13	37	
Rotoehu ash	4.56	0.640	0.620	0.291	484	2194	60	58	37	36	

North Island of New Zealand (analyses published by Duncan & Taylor 1968) and two titanomagnetite standards used by these workers were reanalysed and except for slight drift of Co, Ni and Cu were found to plot on the working curves obtained from successive dilutions of the standard mix.

The artificial standards prepared are close in composition to the unknowns, and hence the absolute values given in Table 3 are generally considered to be accurate. However, in order to overcome any possible 'matrix effects' which may still affect the absolute values, the data used for comparison and identification of the tephra-layers studied are recorded as ratios of X-values (see results below).

Results

After studying X-values and absolute values of all elements analysed, a number of methods were tried to distinguish different tephra-layers. It was found that the ratios of X-values for Ti/V, V/Mn and Co/Mn were the most useful. Results are shown graphically in Figs. 1 and 2.

Rerewhakaaitu tephra comprises a phenocryst-rich and a phenocryst-poor pumice (Cole 1969) which are plotted separately (10A and 10B) and occupy separate fields in Figs. 1 and 2.

The distribution and isopachs of the tephra-layers studied have been described by Baumgart (1954), Healy, Vucetich & Pullar (1964) and Vucetich & Pullar (1969). The isopach map of the Kaharoa Ash (Healy et al. 1964)

* Ti % recorded as TiO_2 %.

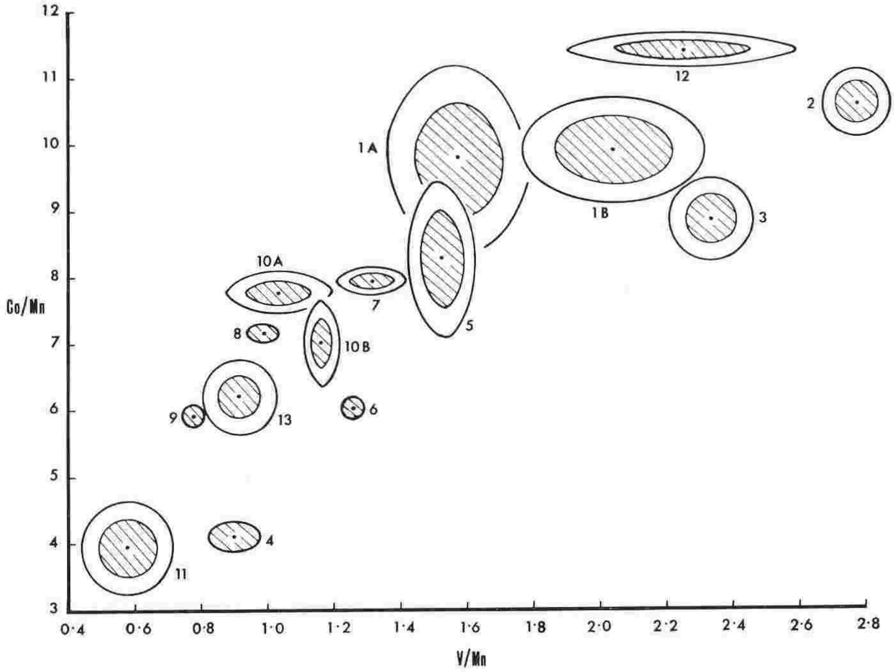

Fig. 1. Diagram of X′ values of titanomagnetites from fifteen numbered New Zealand tephras showing Co/Mn ratios plotted against V/Mn ratios. X′ is the antilog of an X ratio. Each tephra is represented by a dot showing its mean value, by a shaded area that includes 68% (1 s.d.) of its plotted points, and by an outer line that includes 90% (1.645 s.d.) of its plotted points. Only two samples were taken for tephras 4, 6, 8, and 9, and for these the shaded area gives the mean deviation and not the 68% value (1 s.d.).

1A = Kaharoa northern lobe, 1B = Kaharoa south-eastern lobe, 2 = Taupo lapilli, 3 = Waimihia, 4 = Rotokawau, 5 = Whakatane, 6 = Mamaku, 7 = Rotoma, 8 = Waiohau, 9 = Rotorua, 10A = Rerewhakaaitu phenocryst-rich, 10B = Rerewhakaaitu phenocryst-poor, 11 = Oruanui, 12 = Mangaoni, 13 = Rotoehu.

shows a northern and a south-eastern lobe. Figs. 1 and 2 show that the titanomagnetite composition of the two lobes is different.

Except for a slight overlap between the northern lobe of the Kaharoa ash and the Whakatane ash at the 90 % confidence level in Fig. 2, all tephra-layers are distinguished when Figs. 1 and 2 are considered together. It should also be noted that the other elements analysed provide an additional check (see Table 3). Zr however is of limited value as it varies quite markedly in some tephra-deposits and becomes depleted in all samples from paleosols and swamps.

The Tarawera tephra comprising black basaltic scoria and ash and the Loisels Pumice which is distinctively banded were not analysed in detail, as they can both be readily distinguished in the field.

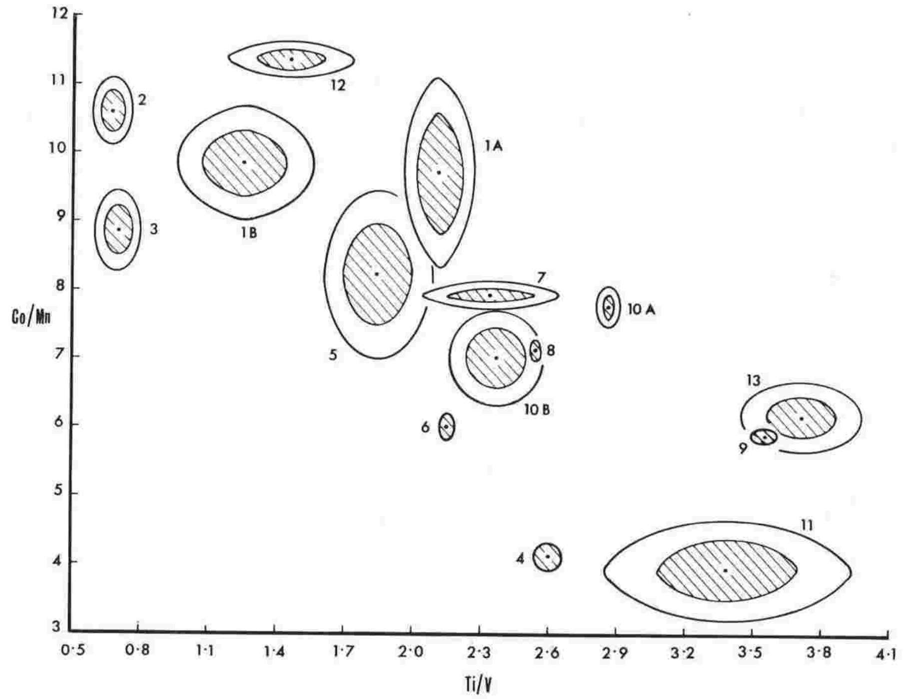

Fig. 2. Diagram of X′ values of titanomagnetites from fifteen numbered New Zealand tephras showing Co/Mn ratios plotted against Ti/V ratios. Description of the diagram and tephra numbers are identical to those given for Fig. 1.

Conclusion

It has been shown that fifteen important Late Qaternary tephra-layers from the North Island of New Zealand can be distinguished by their titanomagnetite composition. The technique is reasonably rapid and titanomagnetite from seven samples can be separated, purified and analysed in triplicate in three days. As titanomagnetite is not readily weathered the method can probably be extended to older and more weathered tephra-deposits. A further probable application is in correlating all the products of a single eruptive episode – tephra, lava, ignimbrite etc.

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Important papers dealing with tephra identification which have been published or come to the author's notice since Kohn (1970), are:

tephrochronology reviews (Kobayashi 1969a,b), thermo-magnetic properties of ferromagnetic minerals in pumice (Kobayashi and Momose 1969, Momose and Kobayashi 1972), applications of instrumental neutron activation analysis (Harward and Youngberg 1969, Harward and Borchardt 1971, Borchardt and Harward 1971, Borchardt et al 1971, Borchardt et al 1972, Randle et al 1971), petrographic and chemical applications (Izett and Wilcox 1968, Izett 1969, Wilcox et al 1970, Izett et al 1970, Izett et al 1970, Izett et al 1971, Binns 1972a,b), microprobe analyses of glass and iron-titanium oxides (Smith et al 1969, Westgate et al 1970, Lerbekmo and Smith 1972, Westgate 1972) and fission-track dating of glass shards (MacDougall 1970, Boellstorff 1972).

Since the averaged analyses of 71 titanomagnetite analyses were presented by Kohn (1970), a further 300 analyses on a total of 36 tephras have been carried out. These additional analyses have shown that the matrix of titanomagnetites being studied does not vary markedly, and that emulsion gamma values can vary between different batches of photographic plates. As plates were calibrated individually for gamma and as standards were exposed on each plate to check for working curve drift, when comparing titanomagnetite compositions, absolute values are now preferred to X' values.

All titanomagnetite analyses are given in Appendix II and averaged results (±1 s.d.) for all tephras are given in Table 6.

Most tephras can be distinguished when differences in ferromagnesian assemblage, titanomagnetite chemistry and to a lesser extent fresh pumice chemistry are used together (Fig 3). The use of dominant ferromagnesian assemblages allows more definite identification of some tephras, which were not always clearly distinguishable when using only titanomagnetite X' values (Kohn 1970).

The most useful elements in titanomagnetite for identification are Ti, V and Cr and less importantly Zr, Co, and Ni. Of these elements, V and Cr are the most useful because they occur in appreciable amounts and cover a wide range of concentrations, V ranging from 400-4,000 ppm and Cr 10-450 ppm.

TEPHRA	No. of Analyses	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
Rotomahana Mud	1	4.70	0.95	0.63	1.22	1518	141	35	39	328	40
Tarawera Lapilli	1	5.42	1.05	0.60	0.91	1251	72	27	73	289	47
Loisels Pumice	7	6.06±1.22	1.28± .31	0.60± .13	0.90± .26	1578±648	72±56	102±29	71±35	44±16	87±36
Kaharoa Ash	28	5.71± .50	0.54± .13	0.83± .17	0.46± .21	1242±251	53±23	37±9	34±12	859±354	52±10
Taupo Pumice	14	7.72± .66	0.87± .15	0.76± .11	0.63± .24	865±341	140±29	37±16	46±19	75±15	57±25
Rotongaio Ash	3	7.80± .16	0.80± .04	0.91± .15	0.31± .14	933±278	137±17	35±14	48±7	161±6	50±9
Putty Ash	2	7.29± .10	0.69± .03	0.71± .04	0.57± .18	1100±111	100±1	44±5	59±2	96±17	51±3
Hatepe Lapilli	8	7.88± .61	0.82± .11	0.69± .10	0.55± .10	1037±317	123±23	38±6	50±14	89±14	56±20
Mapara Tephra	8	7.45± .45	0.78± .08	0.79± .08	0.43± .15	605±121	97±17	35±5	36±10	89±10	50±8
Whakaipo Tephra	7	8.51±1.12	0.55± .06	0.84± .10	0.32± .07	543±176	80±17	38±4	33±10	420±146	63±15
Waimihia Lapilli	16	8.54±1.03	0.83± .22	0.70± .14	0.46± .27	850±172	132±23	36±12	56±20	277±76	57±25
Rotokawau Ash	5	6.02± .54	0.65± .06	0.77± .15	0.17± .07	1972±172	124±44	66±9	62±11	499±42	45±9
Whakatane Ash	18	5.38± .53	0.58± .13	0.67± .09	0.19± .09	1295±103	68±23	43±9	38±19	945±361	38±12
Whangamata Ash	4	6.21± .17	1.08± .09	0.82± .07	0.13± .02	2729±391	291±60	96±9	151±50	176±53	90±10
Hinemaiaia Ash	6	7.10± .66	0.66± .14	0.68± .09	0.29± .23	933±178	91±8	44±9	53±19	304±188	76±14
Mamaku Ash	10	5.06± .22	0.58± .06	0.68± .11	0.20± .09	1536±170	86±17	53±4	35±7	979±148	39±14
Rotoma Ash	14	4.85± .38	0.66± .06	0.74± .05	0.14± .04	1518±137	50±15	48±6	35±9	964±292	27±8
Opepe Tephra	11	7.29± .48	0.90± .28	0.57± .07	0.23± .10	3358±268	112±27	83±21	100±11	271±124	58±16
Poronui Tephra	11	7.07± .81	0.71± .09	0.48± .07	0.22± .12	3283±360	123±41	77±8	103±9	310±180	66±8
Karapiti Lapilli	11	7.12± .39	0.77± .11	0.56± .06	0.17± .10	3633±378	148±48	78±5	119±14	261±113	58±7
Waiohau Ash	11	4.89± .69	0.78± .11	0.72± .07	0.21± .15	1658±180	66±17	51±15	49±22	868±346	37±14
Rotorua Ash	12	5.04± .44	0.90± .11	0.63± .05	0.28± .19	2263±209	171±62	66±17	64±13	549±164	33±15
Puketarata Ash	4	6.10± .44	0.49± .06	0.72± .06	0.29± .22	2090±331	185±41	64±14	72±15	312±94	60±4

TEPHRA	No. of Analyses	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
Rerewhakaaitu Ash (phenocryst rich and bulk analyses)	11	4.99± .35	0.65± .12	0.71± .08	0.22± .17	2096±252	181±49	61±14	60±17	704±260	36±8
Rerewhakaaitu Ash (phenocryst poor)	1	4.83	0.64	0.60	0.24	1404	45	36	31	732	24
Okareka Ash	2	4.55± .37	0.66± .04	0.61± .01	0.08± .03	2137±203	143±8	57±3	55±5	637±121	33±4
Te Rere Ash	2	4.83± .43	0.87± .09	0.72± .07	0.10± .04	1680±77	63±6	50±1	44±6	655±110	32±15
Oruanui Formation	18	5.79± .49	0.76± .13	0.53± .08	0.33± .27	2855±442	241±85	77±10	95±36	269±114	50±19
Aokautere Ash	8	5.81± .45	0.78± .06	0.49± .03	0.41± .14	2454±171	219±63	75±9	83±11	433±140	41±10
Oruanui Formation + Aokautere Ash	26	5.80± .47	0.76± .11	0.52± .07	0.36± .23	2732±421	234±78	76±10	92±31	320±142	47±17
Mangaone Member (E)	7	5.20± .23	0.81± .08	0.81± .09	0.08± .04	1250±397	33±20	37±12	34±14	598±261	35±9
Mangaone Member (D)	3	4.80± .14	0.83± .09	0.77± .04	0.07± .01	1237±337	18±4	38±15	28±5	911±186	25±10
Mangaone Member (C)	14	4.24± .38	0.89± .14	0.74± .07	0.14± .09	1303±333	36±27	42±13	39±18	696±335	23±7
Mangaone Member (B2)	7	4.91± .34	1.30± .16	0.61± .06	0.12± .04	2508±128	77±27	83±14	72±10	100±35	32±12
Mangaone Member (B1)	7	5.26± .31	1.37± .19	0.63± .04	0.32± .17	1755±167	28±7	67±9	45±8	73±14	25±8
Mangaone Member (A)	6	4.84± .26	0.89± .25	0.44± .06	0.14± .04	3411±198	222±47	105±15	108±10	321±96	28±13
Earthquake Flat Breccia Formation	8	5.29± .59	0.55± .07	0.61± .06	0.25± .18	2541±197	198±29	68±4	71±9	567±296	34±9
Rotoiti Breccia Formation	22	4.30± .25	0.72± .04	0.67± .05	0.28± .30	2269±201	70±12	66±10	55±10	358±176	22±7

Table 6. - Averaged titanomagnetite analyses (± 1 s.d.) of < c. 44,000 yr B.P. central North Island tephras. A complete list of analyses is given in Appendix II. Where only two samples have been analysed from a tephra the ± is a mean deviation and not 1 s.d. Values are in ppm unless otherwise indicated. Analysis of samples in Appendix II are the averaged composition of samples which have generally been run in triplicate. Samples were analysed at Chemistry Division, D.S.I.R. using a Hilger-Littrow optical spectrograph. Operating conditions are given by Kohn (1970). The analytical precision, expressed as a relative deviation was approximately ± 10%.

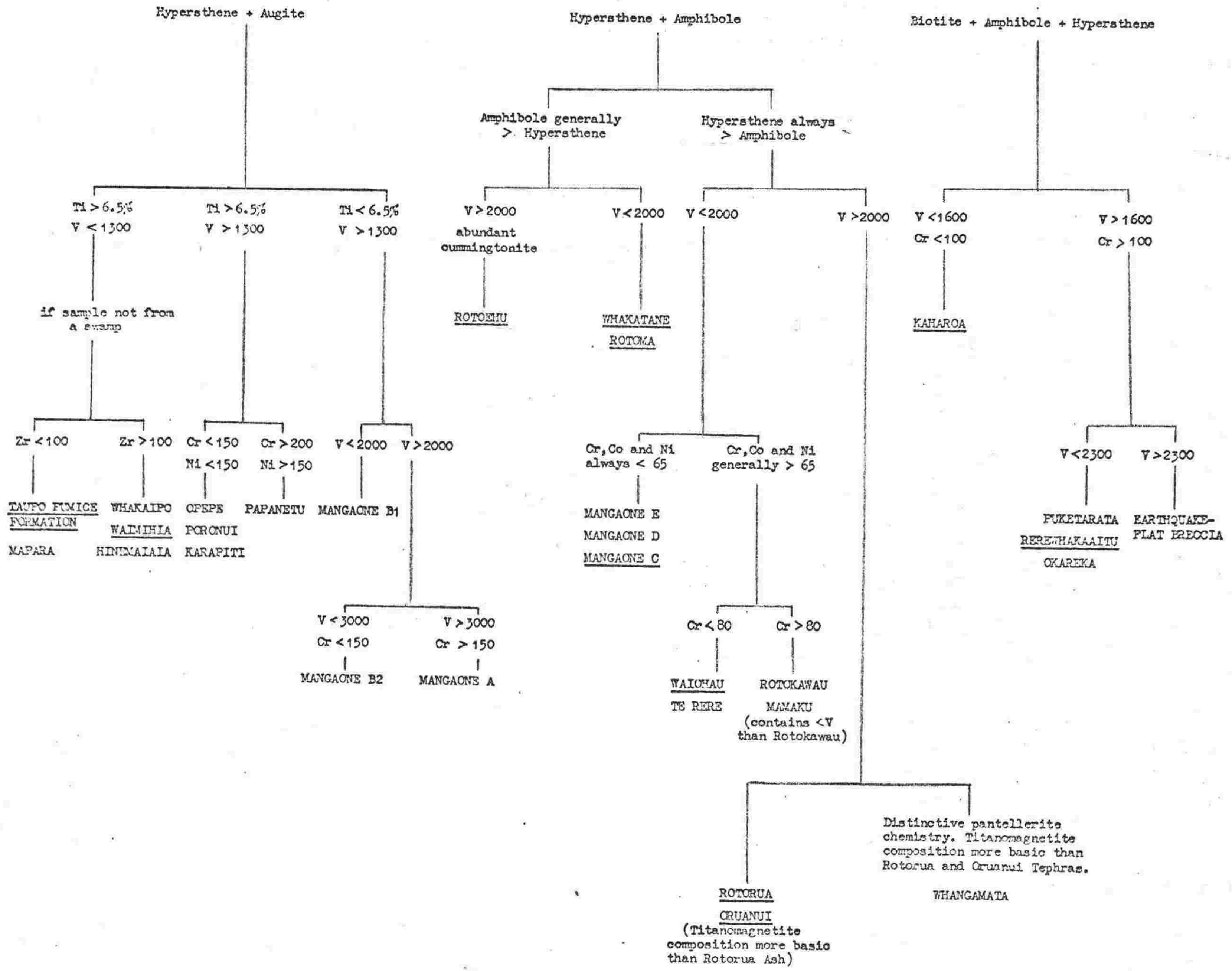


Fig. 3. - Generalised identification scheme for acidic tephras erupted from Taupo Volcanic Zone over the past c. 44,000 yr B.P. using dominant ferromagnesian mineralogy, elemental abundances in titanomagnetite (all values in ppm unless otherwise indicated) and to a lesser extent bulk pumice chemistry. Important tephra marker beds are underlined.

B. APPLICATIONS AND LIMITATIONS OF TEPHRA IDENTIFICATION METHODS - SOME CASE HISTORIES AND MISCELLANEOUS STUDIES

Introductory Statement

In order to test the suitability of methods for tephra identification outlined in Fig 3, a number of studies or case histories have been carried out.

Some of the studies have been carried out jointly. In all cases, the writer's part in these studies has been primarily concerned with the sections on tephra identification and the interpretation of these data.

Studies carried out jointly are outlined below, and an indication is given of the share of the work carried out by each of the authors:

1) Air-Fall Taupo Pumice, Kaharoa Ash and Sea-Rafted Taupo and Loisels Pumice, East Coast North Island, New Zealand.

The laboratory study described in this section was undertaken entirely by Kohn and forms part of a manuscript which will be combined with detailed field studies by Messrs. W.A. Pullar and J.E. Cox, N.Z. Soil Bureau.

2) Ashes, Turbidites and Rates of Sedimentation on the Continental Slope off Hawkes Bay.

Collection and description of cores was completed by Dr K.B. Lewis, N.Z. Oceanographic Institute. Ash identifications and conclusions drawn from them by Kohn. The section forms part of manuscript submitted to N.Z.J. Geol. Geophys. More detailed descriptions of sediments and foraminifera can be found in Lewis (1971).

3) The Stratigraphic Significance of a Dated Late Pleistocene Ash Bed, Near Amberley, South Island, New Zealand.

This section forms part of a manuscript to be combined with detailed field and pedological studies by Mr C.G. Vucetich, Victoria University.

4) Relation of the Earthquake Flat Breccia to the Rotoiti Breccia, Central North Island, New Zealand.

Nairn was responsible for most field studies and collection of about 50% of samples for laboratory work; Kohn analysed titanomagnetites, and the results independently confirmed previous conclusions made by Nairn (1971). Sites described, have all been examined by Kohn.

Two co-authored manuscripts dealing with tephrochronology are presented in Appendices III and IV. These studies form parts of Ph.D. studies undertaken by Messrs. Topping and Neall (Victoria University) respectively. Kohn's part in these studies was to assist in collection of samples, apply identification techniques and write at least 50% of each manuscript.

5) Appendix III - Rhyolitic Tephra Marker Beds in the Tongariro Area, North Island, New Zealand.

For this work Topping collected samples for ^{14}C dating, mapped andesitic tephras and collected most samples from the Tongariro Area for laboratory work; Kohn collected some samples and analysed all titanomagnetites. Ferromagnesian mineralogical determinations and final identifications were made jointly. An appendix of reference sections measured by Topping, included in the final manuscript submitted to N.Z.J. Geol. Geophys. is not given here.

6) Appendix IV - Identification of Late Quaternary Tephras Dating Taranaki Lahar Deposits.

Neall established the stratigraphic column with ^{14}C dates (Neall 1972), studied the mineralogy and collected 75% of samples. Titanomagnetite analyses and some tephra collections were made by Kohn; interpretation of data and conclusions were derived jointly.

1. HOLOCENE AIR-FALL TEPHRA AND SEA-RAFTED PUMICE, EAST COAST, NORTH ISLAND, N.Z.

Introduction

In his coastal reconnaissance of the North Island of New Zealand, Wellman (1962) established the following tephra and sea-rafted pumice stratigraphy from the northern and eastern part of the island.

Kaharoa (air-fall)	930 ± 70 yr B.P.
Loisels Pumice (= dark grey, very gray and black in this study)	c. 1250 yr B.P.
Light coloured Loisels Pumice (grey Loisels Pumice in this study)	c. 1250 yr B.P.
Ohui Ash (air-fall)	c. 1450 yr B.P.
Taupo Pumice (sea-rafted)	c. 1800 yr B.P.
Taupo Pumice (air-fall)	1840 ± 50 yr B.P.
Leigh Pumice (sea-rafted)	c. 1950 yr B.P.

The air-fall tephra stratigraphy, however, is not in accord with that obtained by Vucetich and Pullar (1964). Ohui Ash which was noted by Wellman, particularly at Onewhero Bay, Northland; north end of Opoutere Beach, Coromandel (type locality) and at Wainui Rd, Ohiwa Harbour, Bay of Plenty was not recorded by Vucetich and Pullar (1964). A probable terrestrial limit of Ohui Ash is shown by Wellman (p. 34) to stretch from Onewhero Bay in the north to near Taupo and Wairoa in the south (see Fig 4 for all localities described in this study).

The purposes of this study are to determine whether Ohui Ash is a valid tephra formation and to re-examine the age of the sea-rafted Loisels Pumice in the light of ^{14}C dates determined since Wellman's (1962) paper.

Air-Fall Tephra

Air-fall tephra stratigraphy in coastal and inland sections from Lake Poukawa to Waihi Beach is well documented (Green and Pullar 1960, Wellman 1962, Vucetich and Pullar 1964,

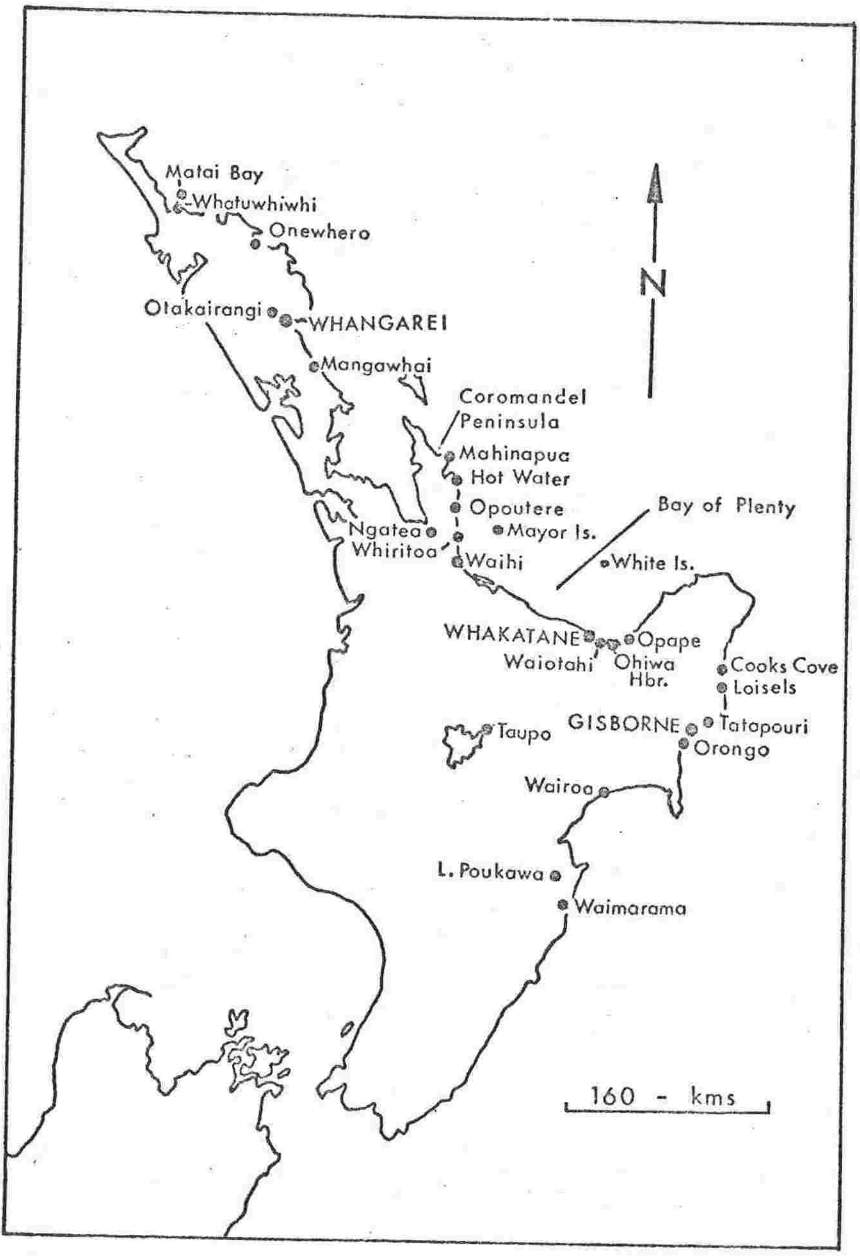


Fig. 4. - Map showing location of sampling sites for study of coastal, sea-rafted pumice and air-fall tephra.

Pullar 1967, Pullar and Penhale 1970, and Pullar and Selby 1971). Individual tephra have now been confirmed by mineralogical examination (Table 7).

North of Waihi Beach, Kaharoa Ash and Taupo Pumice have now been identified. Kaharoa Ash was correlated at a number of coastal sections, and in near-coastal swamps (Table 7, Fig 4). Identifications were made on the presence of abundant biotite in the ferromagnesian assemblage. Confirmation of these identifications by other methods came from a ^{14}C date of 850 ± 50 yr B.P. from peat enclosing a biotite-bearing ash at Otakarangi Swamp, Whangarei (J.E. Cox pers.comm.) and a titanomagnetite composition, similar to the Kaharoa average (Table 6) from a biotite-bearing ash at Te Arai Point, Mangawhai, Northland (Table 7). No other biotite-bearing ashes examined from sections north of Waihi Beach contained enough titanomagnetite for chemical analysis. Taupo Pumice was identified mineralogically from a swamp at Ngatea (Table 7) and possibly at Onewhero Beach.

For correlation purposes Wellman's section 22 at Wainui Rd was the most important on the coastal strip bordering Bay of Plenty. At this section Wellman's sea-rafted pumice and tephra stratigraphy is abbreviated as follows:

Loisels Pumice (dark grey) (sea-rafted)
Loisels Pumice (grey) (sea-rafted)
?Ohui Ash (air-fall)
?Taupo Pumice (sea-rafted)

This section on a low bank bordering Ohiwa Harbour has now been destroyed, probably by high sea levels generated by the Chilean earthquakes in 1960 (W.A. Pullar pers. comm.).

Wellman (p. 52) also discussed stratigraphy at nearby sections on the southern side of the spit at Port Ohope on the northern side of Ohiwa Harbour. He mentioned Taupo Lapilli overlying stumps on the floor of the harbour. The same site was later examined by W.A. Pullar (pers. comm.) who noted sea-rafted Loisels Pumice (dark grey) and sea-rafted Loisels Pumice (white and grey) overlying air-fall lapilli thought to be Taupo Lapilli by W.A. Pullar. However, upto 50% of the

SAMPLE EXAMINED	LOCALITY	NZMS 1 GRID REFERENCE (DATE)	COLLECTOR	ANALYSES 1	ANALYSES 2
		SEA-RAFTED DEPOSITS			
Loisels Pumice (v. dark grey)	Tatapouri Beach, Gisborne District	N98/519389 (1957)	B.P. Kohn	x	-
Loisels Pumice (" " ")	Waimarama Beach, Hawkes Bay District	N142/442985 (1969)	H.W. Wellman	x	-
Loisels Pumice = Taupo Pumice	Whiritoa Beach, south end, Coromandel Peninsula	N53/393079 (1957)	B.P. Kohn	x	-
Loisels Pumice (dark grey) (Wellman's section 9)	Whatuwhiwhi, Northland	N7/912975 (1964)*	H.W. Wellman	x	-
Loisels Pumice (dark grey - black)	Port Chope, Bay of Plenty	N69/570209 (1964)	W.A. Pullar	x	x
Loisels Pumice (grey, white) = Taupo Pumice	" " " " "	" " "	" "	x	x
Loisels Pumice (v. dark grey)	Ocean Beach, Whangarei Heads	N24/073852 (1968)**	J.E. Cox	x	x
Loisels Pumice (white) = Taupo Pumice	" " " "	" " " *	" "	x	x
Loisels Pumice (white) = Taupo Pumice	Opoutere Beach, north-end (Ohui) Coromandel Peninsula	N49/377331 (1967)*	B.P. Kohn	x	x
Loisels Pumice (dark grey)	Hot Water Beach, Coromandel Peninsula	N44/317599 (1966)	A. Leahy	-	x
Pumice (brown) ?Leigh	Koaiti Beach, Pataua, Northland	N20/043979 (1964)	J.E. Cox	x	x
		AIR-FALL DEPOSITS			
?Taupo Pumice	Onewhero Beach, Northland	N11/564567 (1969)	J.E. Cox	-	x
?Taupo Pumice (+beach sand)	Pataua, Northland	N20/028985 (1964)	J.E. Cox		x
Ohui Ash = Taupo Pumice (Type section)**	Opoutere Beach, north-end (Ohui)	N49/317331 (1967)	H.W. Wellman	x	x
Ohui Ash = Taupo Pumice**	" " " " "	N49/377331 (1967)	B.P. Kohn	x	x
Ohui Ash = Taupo Pumice	Savage's Farm, Opoutere	N49/373302 (1967)	J.E. Cox & W.A. Pullar	x	x
Taupo Pumice	Ngatea peat factory, Hauraki Plains	N52/951065 (1967)	J.E. Cox	-	x
?Kaharoa Ash	" " " " "	" " "	" "	-	x
Ohui Ash = ?Kaharoa Ash (+ beach sand) (Wellman's section 24)	Whiritoa Beach, south end	N53/392074 (1957)	J.E. Cox & W.A. Pullar	-	x
Kaharoa Ash	Tikipunga, Whangarei, Northland	N20/826018 (1964)	J.E. Cox	-	x
Kaharoa Ash	Te Arai Point, Mangawhai, Northland	N29/150446 (1969)*	J.E. Cox	x	x
Kaharoa Ash	Otakairangi Swamp, Whangarei	N20/695111 (1964)	J.E. Cox	-	x
Ohui Ash = Kaharoa Ash	Onewhero Beach (swamp)	N11/567558 (1959)	J.E. Cox	-	x
Kaharoa Ash	Marsden Point, Northland	N24/002814 (1968)	J.E. Cox	-	x
Kaharoa Ash	Ngaratunua, Northland	N20/772024 (1964)	J.E. Cox	-	x

Kaharoa Ash	Waihi Beach (swamp)	N53/421928 (1965)	J.E. Cox	-	x
Kaharoa Ash	Kairua, Bay of Plenty	N58/726570 (1965)	J.E. Cox	-	x
Kaharoa Ash	Court's Farm, Pukehina, Bay of Plenty	N68/002426 (1967)	J.E. Cox	-	x
Kaharoa Ash	Pikowai, Bay of Plenty	N68/125378 (1967)	B.P. Kohn	-	x
Kaharoa Ash	Port Ohope, (Ohiwa Harbour) Bay of Plenty	N69/556212 (1969)	W.A. Pullar	-	x
Kaharoa Ash	Lowrey's Rd, Waiotahi, Bay of Plenty	N78/623186 (1962)	W.A. Pullar	-	x
Kaharoa Ash	Near Opape (in peat swamp), Bay of Plenty	N70/829212 (1970)	W.A. Pullar	-	x
Kaharoa Ash	Lovelock's Farm, Ormond, Gisborne Plains	N98/299523 (1957)	W.A. Pullar	-	x
	BEACH AND DUNE SANDS				
Sand, present beach	Opoutere Beach, north end (Ohui)	N49/378331 (1967)	J.E. Cox & W.A. Pullar	x	x
Sand adhering to Loisels Pumice (=Taupo Pumice)	" " " " "	N49/377331 (1967)	J.E. Cox & W.A. Pullar	x	x

* Grid reference approximate (open area with poor local topographic control).

**Deposit slightly water-sorted during wave erosion of dune originally mantled by Taupo Pumice.

1 Titanomagnetite separated, and then analysed by optical emission spectroscopy (<u>see</u> Table 8). }

2 Ferromagnesian minerals separated, and then identified by petrological microscope. } Analyses by B.P. Kohn

Table 7. - Location of samples of Holocene coastal, sea-rafted pumice, air-fall tephra and dune sands, northern and eastern North Island, New Zealand.

ferromagnesian assemblage of this air-fall lapilli contains calcic-hornblende and biotite. This assemblage suggests correlation with Kaharoa Ash and not Taupo Pumice. All pumice lapilli examined for ferromagnesian mineralogy in this study were sieved, and then placed in an ultrasonic vibrator to remove any loose adhering and grain contaminants.

In his sections 20 and 21 at Opape and Waiotahi estuary respectively, Wellman has tentatively correlated an air-fall tephra with Kaharoa Ash. This correlation is probably substantiated by the abundance of biotite in tephra taken from peat swamps near Opape and Waiotahi. At nearby section 22 (Wainui Rd) however, Wellman introduced Ohui Ash, presumably because it underlies Loisels Pumice, but this tephra is now considered to be Kaharoa Ash. As this section has been destroyed there is no way of checking the Ohui Ash/Kaharoa correlation.

At the type locality for Ohui Ash - the north end of Opoutere Beach - grey and dark grey Loisels Pumice overlies an air-fall lapilli (=Ohui Ash). Samples of Ohui Ash from the type locality at Opoutere Beach were collected independently by H.W. Wellman and the writer. A sample of air-fall lapilli from a nearby swamp (at Savage's Farm, Fig 4) was also examined. The ferromagnesian assemblage of these tephras contain hypersthene plus small amounts of augite. Titanomagnetite analyses of the same samples (Table 8) show that they are similar to the average Taupo Pumice titanomagnetite (Table 6). To check for possible contamination of the lapilli, ferromagnesian assemblage and titanomagnetite analyses were determined from two samples of sand associated with lapilli at Opoutere Beach. The ferromagnesian assemblage contains upto 40% of rounded and smoothed grains of calcic-hornblende (not seen in air-fall lapilli) and the titanomagnetite analyses (Table 8), contain higher amounts of Mg, V, Cr, Co and Ni than the titanomagnetite of air-fall lapilli. These data indicate that samples of lapilli examined were not contaminated by sand grains after cleaning treatment and this suggests that the finding of hornblende in Ohui Ash at Opoutere Beach by Challis (appendix in Wellman 1962, p. 92)

V.U.W. NO.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
	GREY LOISELS PUMICE											
11935	Chiwa Harbour	N69/570212	6.86	0.98	0.85	0.40	536	166	45	63	61	90
	Ocean Beach	N24/073852	7.97	0.87	0.81	0.38	641	98	91	75	43	76
	Opoutere Beach	N49/378331	7.89	0.79	0.83	0.64	794	132	43	73	79	54
	PUMICE ASSOCIATED WITH LOISELS											
11934	Hot-Water Beach	N44/317559	7.41	0.84	0.86	0.19	4245	~1101	114	250	287	87
	"OHUI ASH"											
11933	Opoutere Beach	N49/377331	6.79	0.79	0.63	0.63	579	96	64	38	62	28
	Opoutere Beach (Collected by H.W. Wellman)	" "	8.17	0.75	0.84	0.67	780	132	30	37	61	47
	Savage's Farm, Opoutere	N49/373302	6.88	0.82	0.61	0.11	641	97	48	37	66	38
	SANDS AT OPOUTERE BEACH											
	Sand, present-day beach - Opoutere	N49/378331	7.41	0.55	0.55	0.11	2411	303	85	118	176	53
	Sand adhering to grey Loisels Pumice - Opoutere Beach	N49/377331	9.64	1.18	0.53	0.09	2252	294	85	121	237	87
	?LEIGH PUMICE											
11936	Koaiti Beach, Pataua, Northland, large vesicles	N20/043979	6.71	1.53	1.30	0.41	1280	36	68	24	50	87
	as above, weathered brown pumice, large vesicles	" "	8.18	1.62	1.35	0.19	1150	43	68	36	58	76
	KAHAROA ASH											
	Te Arai Pt. Mangawhai, Northland	N29/150446	4.70	0.67	0.73	0.27	1294	61	59	69	241	72

Table 8. - Analyses of titanomagnetites from coastal, sea-rafted pumices, sands and air-fall tephra. Titanomagnetite analyses of Loisels Pumice and further samples of Kaharoa Ash are given in Appendix II. Information on analyses as for Table 6.

was probably due to contamination by sand. No Kaharoa Ash was seen at Opoutere Beach.

At Onewhero Beach, Northland, a biotite-rich, fine, light yellow ash (= Kaharoa Ash) found in a peat swamp just behind the beach (Table 7), undoubtedly correlates with Wellman's Ohui Ash (section 37, p. 60) at an adjacent site.

Refractive indices of glass from Ohui Ash (Wellman, p. 97) range from 1.501-1.503. These values are typical of rhyolitic glass from tephras erupted from the central North Island and support an origin for "Ohui Ash" from Taupo Volcanic Zone.

The air-fall Ohui Ash of Wellman (1962) at Wainui Rd and Onewhero Beach is thus probably Kaharoa Ash, and that at Opoutere Beach is unequivocally Taupo Pumice.

Loisels Pumice

The validity of Ohui Ash as a separate tephra is directly related to the assumption that it is older than "primary" Loisels Pumice deposits. Data presented however, shows that Ohui Ash at different localities maybe either Kaharóa Ash or Taupo Pumice. This finding, together with ^{14}C dates which have come to hand since Wellman's (1962) paper, have prompted a critical re-examination of the age of Loisels Pumice.

Wellman makes a distinction between primary sea-rafted Loisels Pumice which came on to the shore suddenly and in abundance at the time of the eruption and reworked pumice that was deposited later.

Primary Loisels Pumice. According to Wellman (1962, p. 79) typical Loisels Pumice is dark grey when wet and medium grey when dry. 'Primary' Loisels Pumice deposits contain dark grey pumice, often banded (dark and light grey = Wellman's dark grey pumice) and a non-banded light grey pumice. This pale coloured pumice was considered by Wellman to have been erupted from the same source and simultaneously with the banded variety. Based on mineralogy and texture of pumices dredged from near the summits of five seamounts in the vicinity of White Island, Bay of Plenty, Duncan (1970b) suggested that this group of seamounts may have been the source of the Loisels Pumice.

The ferromagnesian assemblage of both types of Loisels Pumice contains hypersthene + augite. Titanomagnetite analyses of the banded pumice are given in Appendix II while those for the light-grey variety in Table 8. The wide range of some elements in the banded Loisels (especially V and Cr) is probably due to the varying contributions of dacite (lighter) and andesite (darker) within samples analysed. The titanomagnetite analyses of the light-grey pumice show generally higher values for Cr and lower values for Mg, V, Co and Ni than in the banded Loisels Pumice. The light-grey Loisels Pumice shows almost identical composition to Taupo Pumice (Table 6 and Appendix II). This pumice is therefore considered to be sea-rafted Taupo Pumice.

Wellman (p. 79) noted primary sea-rafted Loisels Pumice at Opape and Waiotahi Estuary (sections 20, 21) all of which were overlain by tentatively identified Kaharoa Ash. The sections at these sites have since been destroyed by natural processes so that the presence of Kaharoa Ash cannot be confirmed. The only other place where primary Loisels Pumice was found by Wellman in central Bay of Plenty was at Port Ohope where underlying air-fall lapilli appear to be Kaharoa Ash rather than Taupo Pumice. Loisels Pumice would thus appear to be older than Kaharoa Ash at Opape and Waiotahi, and younger at Port Ohope.

During the course of archaeological excavations at Orongo Bay, near Gisborne (Fig 4) (Pullar and Green 1960), a thin white discontinuous ash was noted by W.A. Pullar (pers. comm.) to overlie primary Loisels Pumice. This ash appeared to be similar to biotite-rich ash seen at Ormond, on the Gisborne Plains (Table 7). A re-examination of the Orongo Bay section by W.A. Pullar (pers. comm.) in 1973 however, indicates that Kaharoa Ash is not present.

Secondary Loisels Pumice. Secondary Loisels Pumice is often associated with other types of pumice. Small quantities of a light-grey weakly-banded pumice (11934, Table 8) and a black pumice, are associated with Loisels Pumice at Hot Water Beach (Fig 4). Pumice (11934) contains a hypersthene + augite ferromagnesian assemblage, and differs in titanomagnetite composition from Loisels Pumice and Taupo Volcanic Zone tephras (Table 6). Hence, these pumices are considered by the author to have been erupted from a source outside Taupo Volcanic Zone. They were probably carried to the east coast North Island in a similar way to the South Sandwich Island pumice, which was recently deposited on New Zealand beaches (Coombs and Landis, 1966).

It is probable that the presence of other types of pumice associated with Loisels Pumice (dark grey and light grey varieties) are indicative of secondary Loisels Pumice deposits.

Age. At Hot Water Beach, east coast of Coromandel Peninsula, Leahy (1971) reports ^{14}C dates of 421 ± 40 yr B.P. (NZ 1169) and 484 ± 79 yr B.P. (NZ 1170) for charcoal above Loisels Pumice, and at Mahinapua Bay, Coromandel Peninsula; Golson (in Green 1963) reports a date of 640 ± 50 yr B.P. (NZ 354) for charcoal below Loisels Pumice. At Matai Bay, Merita, Northland, charcoal beneath Loisels Pumice is dated at 799 ± 40 (NZ 396) (Wellman pers. comm.). At Cooks Cove, 40 km NE of Gisborne (type locality for Holocene) charcoal above Loisels Pumice is dated at 519 ± 41 yr B.P. (NZ 631) and totara logs under Loisels Pumice at the base of the section at 925 ± 46 (NZ 651) (^{14}C dates from Wellman, pers. comm.).

Loisels Pumice at Hot Water Beach, although occurring in abundance, coexists with other types of pumice and occurs in an archaeological occupation layer, it is therefore probable that this pumice is reworked or was put there by man. Loisels Pumice at Mahinapua and Matai Bay is also secondary (Wellman 1962). However, at Cooks Cove, Loisels Pumice is considered to be primary, as is Loisels Pumice at Onewhero Beach, Northland (Wellman 1962) where it probably overlies Kaharoa Ash (= Ohui Ash).

Leigh Pumice

At Koaiti Beach, Pataua, Northland a light brown pumice with large vesicles (11936, Table 8) underlying dark grey Loisels Pumice is correlated with the Leigh Pumice (Wellman 1962). This pumice contains a hypersthene + augite ferromagnesian assemblage and differs in titanomagnetite composition from other sea-rafted pumices or Taupo Volcanic Zone tephras (Table 8). Leigh Pumice may have been erupted from the seamounts around White Island (Duncan 1970b).

Conclusions

1) Air-fall Ohui Ash of Wellman is probably Kaharoa Ash at Wainui Road and Onewhero Beach, and is definitely Taupo Pumice at Opoutere Beach (Ohui Ash type section).

2) Grey Loisels Pumice is sea-rafted Taupo Pumice.

3) Available data still does not resolve the relationship between primary Loisels Pumice and Kaharoa Ash. Sections indicating an age older than Kaharoa Ash for the first incoming of Loisels Pumice have now been destroyed by natural processes. There is, however, much evidence to support the age of primary Loisels Pumice as being post-Kaharoa Ash, but this supposition will only become certain when more ^{14}C dates for the first incoming of Loisels Pumice are available.

2. ASHES, TURBIDITES AND RATES OF SEDIMENTATION ON THE CONTINENTAL SLOPE OFF HAWKES BAY

Introduction

Over the last c. 44,000 yrs B.P. several rhyolitic tephras have thickly blanketed the topography of Hawkes Bay Land District (Fig 5). Two of the most conspicuous are the Waimihia Lapilli, 0.3 m thick at Napier (Vucetich and Pullar 1964) and the Oruanui Tephra which is about 1 m thick at Napier (Vucetich and Pullar 1969). Both were erupted from the Lake Taupo Volcanic Centre, Taupo Volcanic Zone (Fig 1) and were blown eastwards to Hawkes Bay. The tephras were also carried further eastwards and are now identified in piston cores taken from the sea-bed to the east of the Hawkes Bay coast.

In general, detrital sediments on the seabed off Hawkes Bay become finer offshore (K.B. Lewis pers. comm.) but the presence of coarse sandy layers, in some of the piston cores indicate alternative methods of offshore deposition during the late Quaternary.

Collection of Cores

Eighteen piston and seven gravity cores were collected from the continental slope (Table 9; Fig 5) at depths ranging from 1,150 to 2,469 m, by Dr K.B. Lewis (Oceanographic Institute) during N.Z. Oceanographic Institute cruises Turnagain I and II. The cores were subsequently described by (Lewis 1971) and samples of ash from them were given to the author for identification.

The piston cores, the longest of which was 2.8 m in length, were collected in 50 mm internal diameter steel pipes and the gravity cores were collected in similar pipes with plastic liners. All cores were extruded when wet and examined when dry.

Description of Cores

The cores consist mostly of pale grey mud with conspicuous

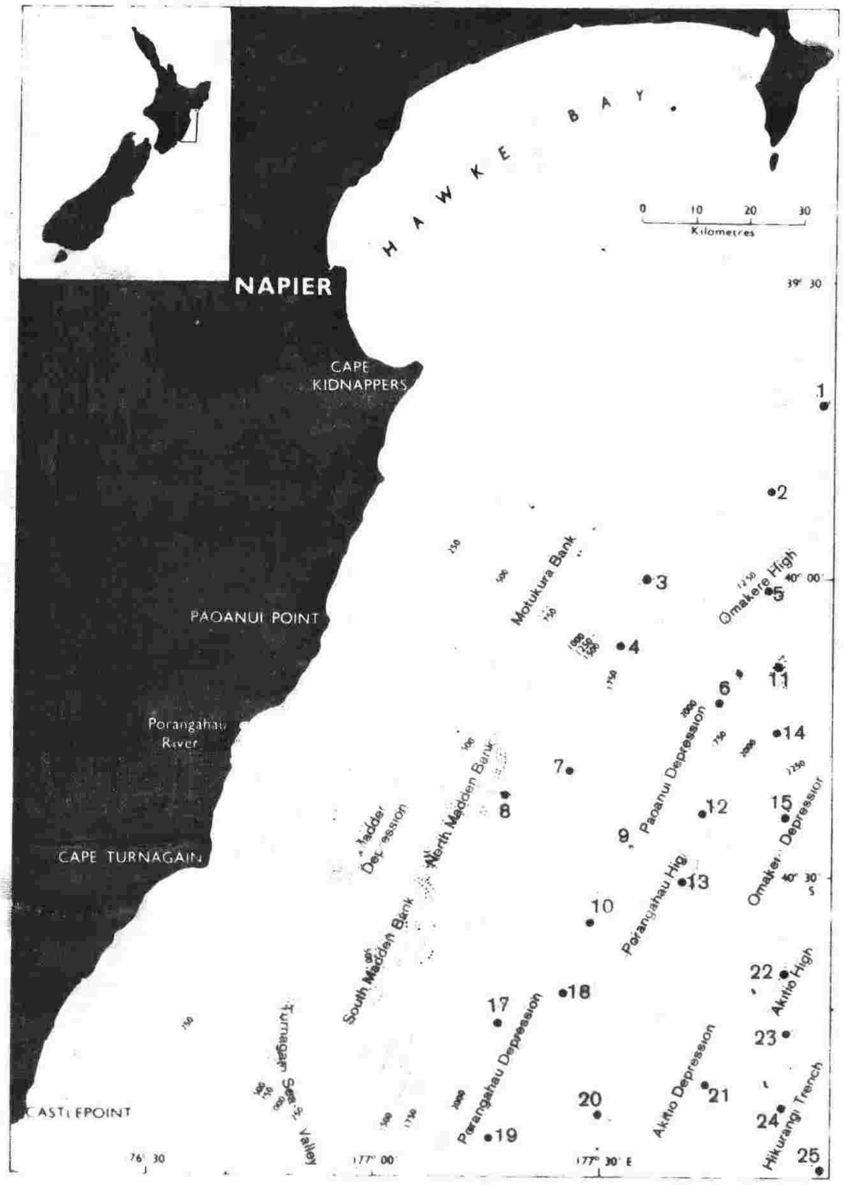


Fig. 5. - Chart of the continental slope off Hawkes Bay Land District showing position of cores. Depth in metres.
Inset: Map of New Zealand showing position of the study area.

Core No.	NZOI Sta.	Latitude S	Longitude E	Depth (m)	Corer type
1	F637	39°41'	177°59'	1010	short gravity
2	F670	39°51'	177°52'	1291	piston
3	F684	40°00'	177°36'	1357	gravity
4	F683	40°08'	177°32'	1646	piston
5	F671	40°02'	177°50'	1169	piston
6	F682	40°13'	177°45'	2127	piston
7	F690	40°19'	177°26'	1726	gravity
8	F721	40°22'	177°16'	1536	gravity
9	F681	40°23'	177°33'	1936	piston
10	F595	40°36'	177°29'	1814	piston
11	F673	40°11'	177°51'	1419	piston
12	F676	40°21'	177°43'	1650	short gravity
13	F680	40°29'	177°39'	1606	piston
14	F674	40°14'	177°54'	2136	piston
15	F679	40°22'	177°65'	2329	piston
16	B885	40°25'	176°56'	1150	piston
17	F597	40°46'	177°18'	2019	piston
18	F596	40°44'	177°25'	2116	piston
19	F594	40°56'	177°14'	2063	piston
20	F593	40°54'	177°28'	2176	piston
21	F592	40°50'	177°42'	2432	piston
22	F678	40°33'	177°50'	2195	short gravity
23	F677	40°44'	177°53'	2012	short gravity
24	F591	40°53'	177°53'	2400	piston
25	F590	40°59'	177°59'	2469	piston

Table 9. - Position of cores from continental slope.

horizons of white ash and dark muddy sand (Figs 6,7). Many of the horizons are bedded layers but others are represented only by sediment in burrows. In many cores a simple cycle of layers is repeated with various modifications. The cycle consists of five types of layer (Fig 8 D), from the bottom upwards,
1. dark sandy mud; 2. dark grey mud with large burrows;
3. dark grey mud with small burrows; 4. pale grey mud;
5. volcanic ash. One or more of the types may be absent because burrowing is rare at some places and volcanic ashes occur in only a few cycles. In the northern part of the study area, sandy layers are rare. In the southern part they are commonly only in depressions that are downslope from the steep channels on the upper continental slope off the Porangahau River.

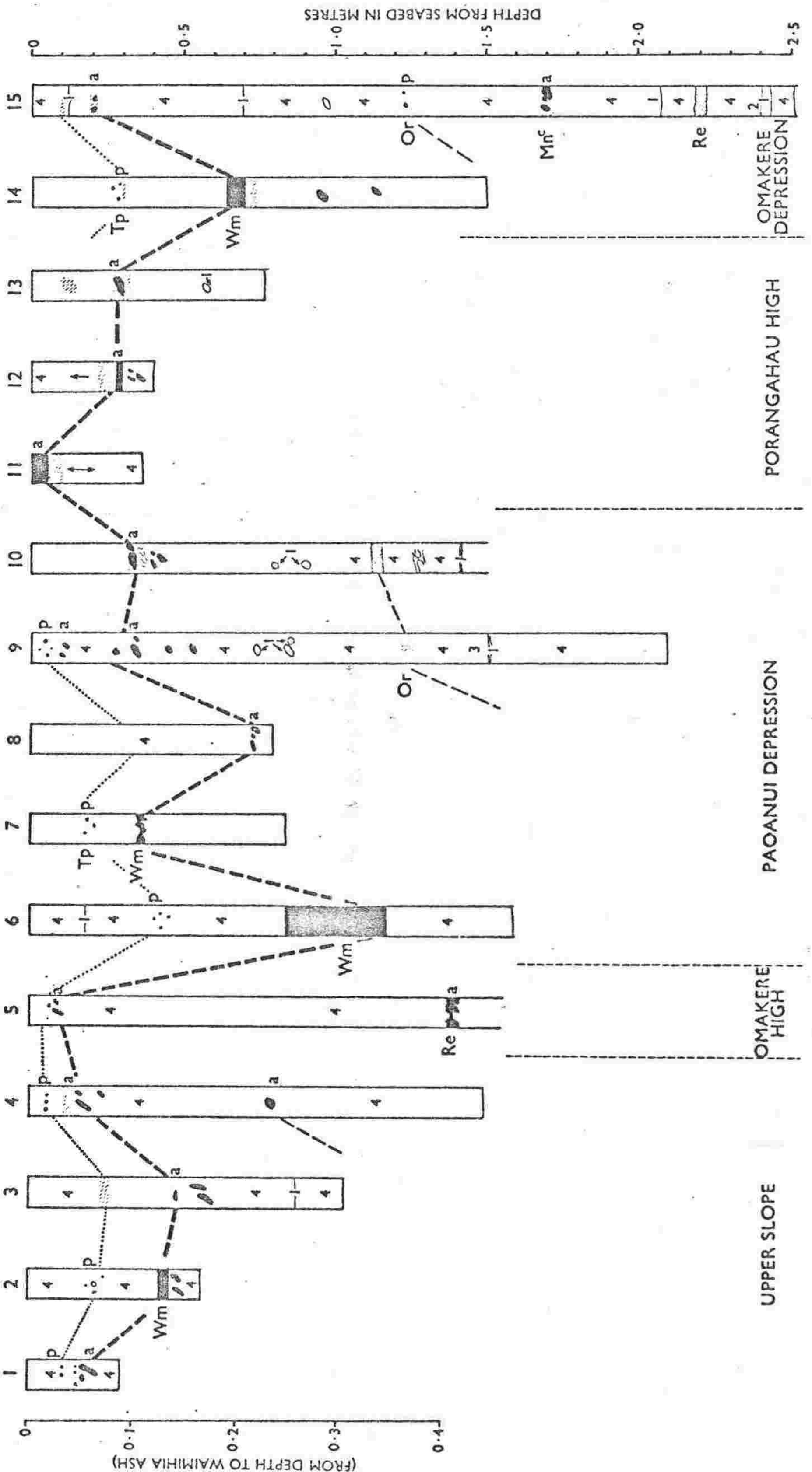
Sandy layers have sharp upper and lower boundaries and range in thickness from 1 mm lamina to a 50 mm thick bed. Sedimentological features within sandy layers are shown in Fig 8 B,C. Most sandy layers contain 10-50% sand grains, comprising subangular detrital quartz and feldspar, and a few heavy minerals and foraminifera. Some sandy layers contain a foraminiferal fauna that includes a significant proportion of small shallow water foraminifera (K.B. Lewis pers. comm.). The mud fraction in the sandy layers is predominantly coarse silt.

Dark grey mud above each sandy layer generally contains <2% sand and 65-75% silt. Dark grey mud grades upwards into pale grey mud. The pale grey "hemipelagic" mud forms the bulk of each core and shows no evidence of bedding and only faint indications of burrowing. Analyses of this sediment show that it contains more clay than the dark grey mud, <2% sand and only 55-65% silt.

There are no more than two clean, white, ash horizons in any core, but there are additional light-grey, muddy, ash horizons in some cores. Many cores also include pumice fragments in a band about halfway between the top ash and the seabed. About half of the clean, white ash horizons are recognised only in the infillings of burrows. The rest are discrete layers, many of which are parallel bedded. All except one of the discrete layers are between 0.02 m and 0.05 m thick. The

Fig. 6. - Diagrammatic sections of cores from the northern part of the study area showing Taupo Pumice (Tp), Waimihia ash (Wm), Oruanui Ash (Or), Mangaone Lapilli Formation member (c) (Mn^c) and Rotoehu Ash (Re). Black is airfall ash, broken line is muddy ash, white is detrital mud and sand, 1 = dark sandy layer, 2 = dark grey sand with either no burrows or large burrows, 3 = dark grey mud with small burrows grading up to 4 = pale grey mud. p = pumice in mud; a = ash.
Scales show depth in core in metres and rates of deposition of sediment overlying Waimihia ash from depth to Waimihia ash.

Fig. 7. - Diagrammatic sections of cores from southern part of study area where turbidites (1,2,3) are common. Notations are similar to those for Fig. 6.
Percentages to left of each section are percentages of sediment coarser than 0.064 mm.
Z indicates those analysed samples with significant proportions of shallow water foraminifera in the sand fraction.


DEPTH FROM SEABED IN METRES
0
0·5
1·0
1·5
2·0
2·5
RATE OF DEPOSITION IN METRES PER THOUSAND YEARS
(FROM DEPTH TO WAIMIHIA ASH)
0
0·1
0·2
0·3
0·4
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Wm
Tp
Or
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UPPER SLOPE
OMAKERE HIGH
PAOANUI DEPRESSION
PORANGAHAU HIGH
OMAKERE DEPRESSION

Fig. 6.

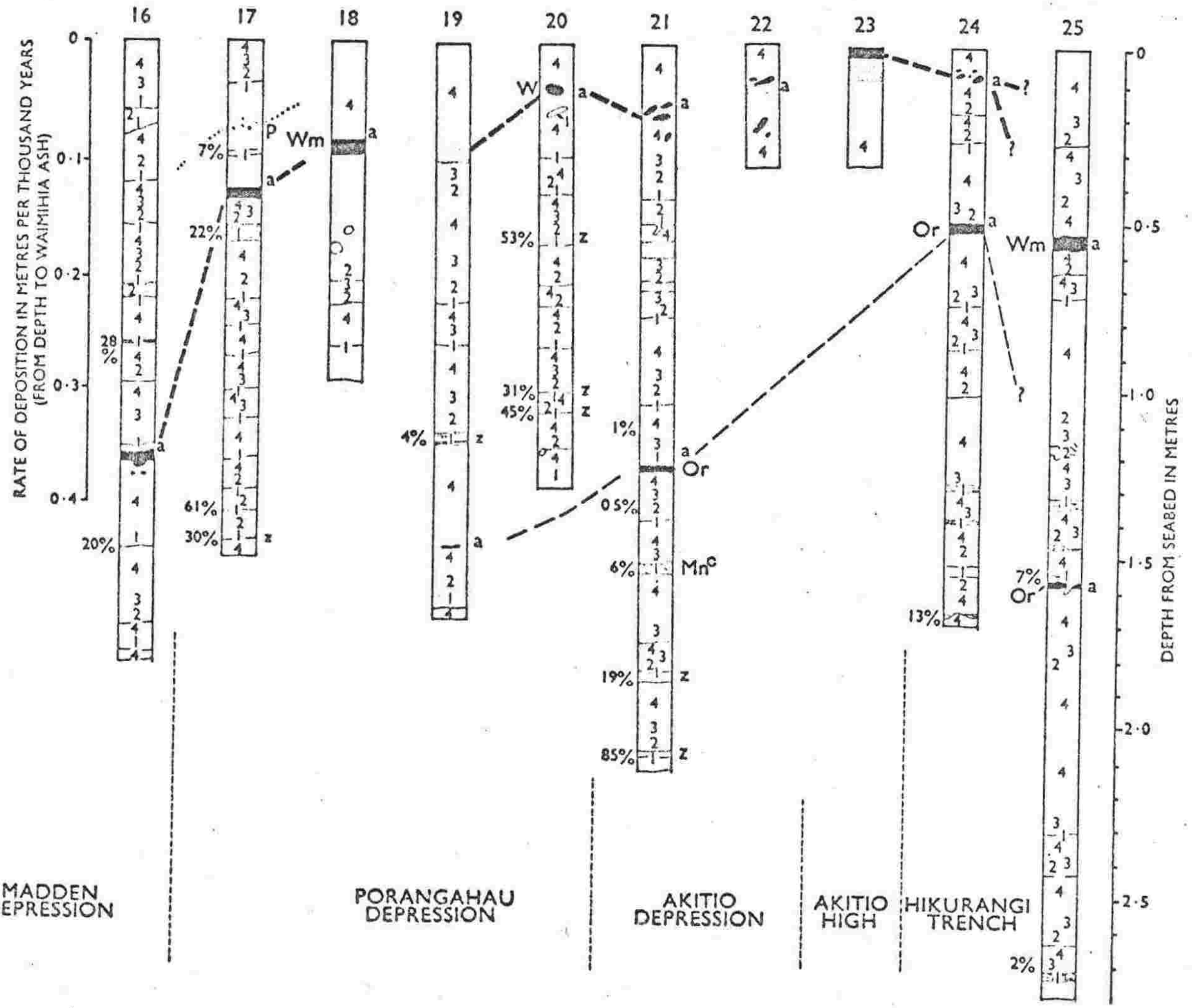
16
17
18
19
20
21
22
23
24
25
RATE OF DEPOSITION IN METRES PER THOUSAND YEARS
(FROM DEPTH TO WAIMIHIA ASH)
0
0·1
0·2
0·3
0·4
DEPTH FROM SEABED IN METRES
0
0·5
1·0
1·5
2·0
2·5
Wm
W
Or
Mn^c
P
a
z
?
28%
20%
7%
22%
61%
30%
4%
53%
31%
45%
1%
0·5%
6%
19%
85%
13%
7%
2%
MADDEN DEPRESSION
PORANGAHAU DEPRESSION
AKITIO DEPRESSION
AKITIO HIGH
HIKURANGI TRENCH

Fig. 7.

exception is 0.34 m thick (in core 6, see Fig 8 A) and consists of a basal layer about 0.01 m thick of moderately coarse, white ash and many overlying bands that grade upwards from coarse ash to fine ash. Some of the overlying bands are discoloured by detrital material. The coarse ashes consist mostly of fine sand-sized, clear glass shards and a few euhedral heavy mineral grains. Fine ashes consist almost exclusively of silt-sized shards.

Correlation and Identification of the Ash Beds

The ashes can be correlated among cores in the study area and with dated tephra horizons on land.

Correlation is relatively simple where tephra stratigraphy in each core is the same. The two youngest horizons, a band of pumice-rich mud and an ash below it can be traced over much of the study area (Figs 6,7), both remaining at similar relative distances below the sea-bed. At some of the deeper stations there is no pumice and the ash is thin or absent, making correlation doubtful.

The Waimihia ash (c. 3,400 yrs B.P.) is the youngest ash that forms a clearly recognisable layer on the adjacent mainland (Vucetich and Pullar 1964) and is likely to correspond to the youngest, well defined, layer offshore, that is the one below the pumice-rich mud. This correlation was tested by examining the ferromagnesian assemblage and chemical content of the titanomagnetite from the ash using the method described on p. 35. Fifteen samples of the ash, nine from cores (Core Nos 2,5,6,7,9,14,18,20 and 25), two from Holocene beach deposits at Waimarama and Kairakau on the adjacent land and four from known Waimihia Lapilli deposits, were examined. The ferromagnesian assemblage of all the samples consists of hypersthene ± traces of augite. This assemblage is identical to that found in Waimihia Lapilli in the Taupo area (Ewart 1963). Sufficient titanomagnetite for chemical analysis was extracted from six of the core samples and all samples on shore. Results are presented in Table 10. The results show that the titanomagnetites from the core samples have rela-

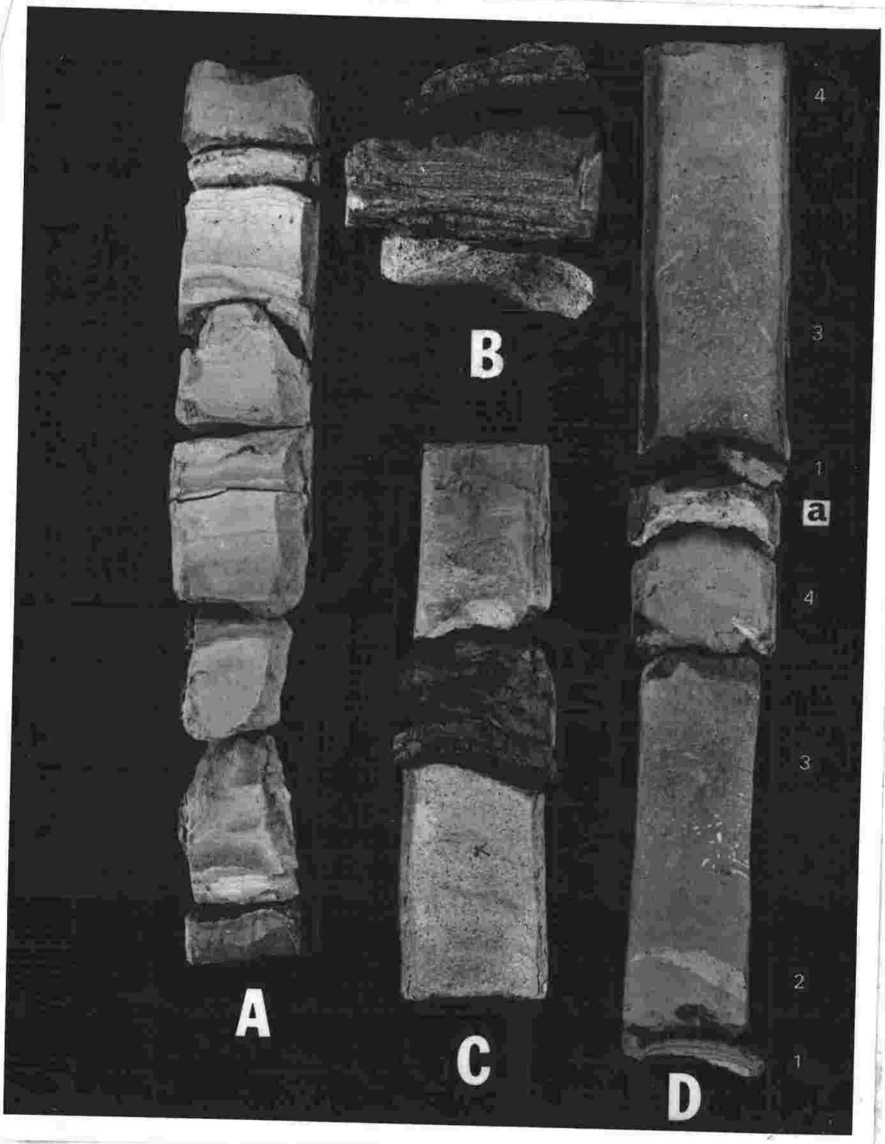

Fig. 8. - Photographs showing segments of cores. A : core 6, at depth in core of 0.82 - 1.20 m, showing bedding, including graded-bedding, in thick layer of Waimihia ash. B : Core 17, at depth in core of 0.56 - 0.60 m, showing parallel and current bedding in sandy layer. C : Core 20, at depth in core of 1.09 - 1.23 m, showing parallel and contorted bedding in sandy layer; below sandy layer is pale grey mud, above sandy layer is dark mud with small (and large) burrows. D : Core 22, at depth in core of 1.13 - 1.41 m, showing ideal cycle of sedimentation; from base, 1 = sandy layer, 2 = dark grey mud with large burrows, 3 = dark grey mud with small burrows, 4 = pale grey mud, a = ash; there is a similar cycle, without 2, above the ash.

tively high titanium, chromium and zirconium values and low vanadium and cobalt values and are therefore similar to those from positively identified Waimihia Lapilli onland (Table 10) and different from those from other widespread ashes (Table 6 p. 38). The zirconium value which are generally >100 ppm, identify the tephra as Waimihia rather than Taupo Pumice, which is similar both chemically and mineralogically but generally contains <100 ppm zirconium (Tables 6 and 10).

Titanomagnetite from the uppermost ash in core 25 contains anomalously low titanium and high nickel but it is otherwise similar to Waimihia Lapilli. The band of pumice fragments that lies about halfway between Waimihia ash and the seabed can be reasonably supposed to be about half the age of the Waimihia ash, i.e., about 1,700 yrs B.P. It is therefore correlated with the c. 1,800 yrs B.P. Taupo Pumice Formation (Healy 1964). A sample of pumice from core 9 did not yield enough titanomagnetite for chemical analysis, but the presence of hypersthene as the only ferromagnesian mineral is consistent with its identification as Taupo Pumice.

In eight of the longest cores from the lower continental slope there are layers of muddy ash, muddy pumice and clean white ash beneath the Waimihia ash. A maximum of three such layers occur in core 15. The first ash stratigraphically below the Waimihia ash is a clean white ash in cores 4,19,21, 24 and 25 and is a mixture of mud and ash in cores 9,10 and 15. In six of the eight cores this ash is between 5 and 7 times deeper below the sea-bed than the Waimihia ash, and assuming constant rates of sedimentation, may be supposed to be between 5 and 7 times older; that is between 17,000 and 24,000 yrs B.P. It is, therefore, correlated with the c. 20,500 yrs B.P. Oruanui Ash which forms the second oldest distinct tephra layer in southern Hawkes Bay Land District (Vucetich and Pullar 1969). Samples of this ash from cores 21 and 24 were examined. Both samples have a ferromagnesian assemblage of hypersthene + calcic-hornblende, which is typical of Oruanui Ash on land (Table 3). In two of the eight cores the ash is only about three times deeper than the Waimihia ash, but is still considered to represent Oruanui Ash. It is probable that rates

SAMPLE	LOCALITY	GRID REF.	Ti %	Mg %	Mn %	Ca %	V	Cr	Co	Ni	Zr	Cu
Waimihia Lapilli	Napier-Taupo Highway	N94/572354	7.28	1.23	0.79	0.67	699	149	24	27	332	41
Waimihia Lapilli	Wairakei-Putaruru Highway (Route 1)	N94/516544	8.02	0.78	0.89	0.46	1023	135	55	68	380	60
Waimihia Lapilli	Napier-Wairoa Road (10-25 cm from top ash)	N114/327763	8.42	0.70	0.59	0.43	653	125	20	34	359	52
Waimihia Lapilli	Poukawa Swamp	N141/141054	9.11	0.64	0.83	0.98	753	123	45	58	105	63
Waimihia Lapilli	Waimarama Beach	N142/407973	6.79	0.74	0.59	0.88	632	101	18	74	226	23
Waimihia Lapilli	Kairakau Beach	N141/338844	8.87	0.77	0.52	0.85	920	145	28	48	109	56
Taupo Pumice	Napier-Taupo Highway basal 30 cm	N94/564354	7.92	1.06	0.69	0.54	649	131	16	27	68	22
Taupo Pumice	Kaingaroa Headquarters	N86/023711	8.16	1.06	0.69	0.57	596	122	16	25	62	35
Core 2	Upper slope off Cape Kidnappers		7.47	0.65	0.79	1.24	696	143	39	60	442	70
Core 6	Paoanui Depression		6.94	1.03	0.90	0.67	939	125	28	51	151	n.d.
Core 7	Paoanui Depression		7.74	0.79	0.55	0.68	812	111	34	59	281	47
Core 18	Porangahau Depression		6.84	0.76	0.51	0.73	826	160	44	75	213	n.d.
Core 20	Porangahau Depression		7.56	0.81	0.90	0.66	825	114	32	56	141	n.d.
Core 25	Hikurangi Trench		3.49	0.59	0.50	0.46	443	155	41	229	99	n.d.

Table 10. - Titanomagnetite analyses of Taupo Pumice and Waimihia Lapilli Formations on-land and Waimihia ash in off-shore cores (values are in ppm unless otherwise indicated). Further analyses of titanomagnetites from Taupo Pumice and Waimihia Lapilli Formations on-land are given in Appendix II. Information on analyses as for Table 6.

n.d. = not determined.

of sedimentation have not been constant at these two sites. None of the ash layers beneath the Waimihia ash contain sufficient titanomagnetite for chemical analysis.

There is an ash-rich layer underlying Oruanui Ash in cores 9 and 15. It is estimated, from its relative depth to the depth of the Waimihia ash, to be about 28,000 to 30,000 yrs B.P. and is correlated with the c. 30,000 yr old Mangaone Lapilli Formation, member (c) (Pullar and Heine 1971) which forms a relatively thick layer on the adjacent land. The ash in core 15 contains a ferromagnesian assemblage of hypersthene + calcic-hornblende, which is characteristic of the three youngest members of the Mangaone Lapilli Formation, members (c), (d) and (e). Members (d) and (e) are younger than the estimated age of the ash, member (d) being 26,300 ± 700 yrs B.P. (N.Z. 867, Vucetich and Pullar 1969) and member (e) younger.

An older ash occurs in cores 5 and 15. It is estimated from its depth relative to the depth of Waimihia ash to be about 38,000 to 46,000 yrs old and is correlated with the Rotoehu Ash member of the Rotoiti Breccia Formation (Nairn 1972). The Rotoehu has been ^{14}C dated at 44,200 ± 4,300 yrs B.P. (67% probability) and >43,700 yrs B.P. (95% probability) (N.Z. 877, Pullar and Heine 1971) and forms a thick and distinctive tephra layer in Hawkes Bay (Vucetich and Pullar 1969). The ferromagnesian assemblage of the ash in core 5, which does not contain ash of the Oruanui and Mangaone Formations, is predominantly cummingtonite with minor amounts of hypersthene + calcic-hornblende. The presence of cummingtonite as the dominant amphibole is characteristic of Rotoehu Ash (Table 3).

Rates of Sedimentation

On the continental shelf off Hawkes Bay, Holocene rates of deposition have been estimated from the depth of burial of dated seismic reflectors (Lewis in press). On the continental slope Holocene reflectors are absent but the top of the Waimihia ash, which is present in all cores, forms a convenient horizon from which rates of sedimentation may be calculated.

The thickness of sediment overlying Waimihia ash ranges from 1.21 m in the Madden Depression to zero on some submarine highs. Thus late Holocene rates of sedimentation range from 0.36 m/1000 yrs to zero.

Sediment above the Waimihia ash is generally pale grey mud, but in four cores (nos. 6,16,17 and 25) from four different depressions it includes dark sandy layers. In core 16 from the Madden Depression there are nine sandy layers above the ash, so that on an average, one sandy layer is deposited there about every 400 years. In core 17 from the Porangahau Depression, which is downslope from the Madden Depression, there are only two sandy layers above the Waimihia ash. In core 25, from the Hikurangi Trench, there are two dark, coarse silty layers above the ash that is tentatively identified as being Waimihia ash. If the ash in core 25 is Waimihia ash then the rate of deposition is about 0.15 m/1000 yrs which is high for a core so deep and so far from land; the rate in adjacent core 24 being only 0.02 m/1000 yrs.

In core 16 the nine dark sandy layers and their overlying dark silts constitute more than half of the total volume of sediment. Pale grey mud is deposited most rapidly in the Paoanui Depression at a rate of 0.23 m/1000 yrs, the Paoanui Depression being on that part of the continental slope closest to the large rivers of Hawkes Bay.

Mode of Deposition of Ash and Sediment

The Waimihia ash blankets the topography on land and beneath the sea. Unlike all other types of sediment except animal skeletons, it is deposited on submarine highs and in submarine depressions. It is considered to have fallen on the sea and settled through the water column to its present resting place. At places where the ash formed a layer more than about 0.02 m thick, it apparently destroyed the local infauna because the ash is preserved as an undisturbed white layer. At places where the ash was thin, animals mixed it with mud so that white ash is preserved only in burrows. The only evidence of redeposition of the ash is in the

Paoanui Depression where it is overthick and contains numerous slightly muddy graded beds (Fig 8 A).

The mode of deposition of sediments has been described by Lewis (1971). Of particular interest are the layers of sandy sediment, some of which are current bedded, indicating that swift flowing currents have crossed the floors of the depressions in the southern part of the study area. The currents have affected depressions in a zone at right angles to the trend of the continental slope and therefore are unlikely to be deep ocean currents. They have deposited coarse detrital sediment including tests of shallow water foraminifera, in flat-floored depressions and appear to be correlated with channels that are incised into the outer continental shelf and upper continental slope. The layers of sandy sediment are thus considered to have been deposited by turbidity currents.

Since deposition of the Waimihia ash 3,400 yrs ago, nine turbidity currents have spread over the Madden Depression and two have reached the Porangahau Depression and probably the Hikurangi Trench. It is likely that the turbidity currents were triggered by earthquakes; at least three major earthquakes that resulted in massive crustal movements, have occurred in southern North Island during the last 3,400 yrs (Wellman 1969). Prior to the deposition of the Waimihia ash many turbidity currents descended to the Akito Depression and to the channelled Hikurangi Trench.

Conclusions

1. Taupo Pumice and ashes of the Waimihia, Oruanui, Mangaone Lapilli and Rotoiti Breccia Formations can be traced more than 100 km seaward off the Hawkes Bay coast.
2. In depressions on the continental slope the Waimihia ash has been buried by pale "hemipelagic" grey mud at rates ranging from 0.02 to 0.23 m/1000 yrs.
3. In depressions downslope from the channels off the Porangahau River Waimihia ash has been buried partly by grey "hemipelagic" mud and partly by dark turbidite layers. Nine turbidite layers overlie the ash in the Madden Depression where the total rate of deposition is 0.36 m/1000 yrs and two turbidite layers overlie the ash in the deeper Porangahau Depression and Hikurangi Trench.

3. THE STRATIGRAPHIC SIGNIFICANCE OF A DATED LATE PLEISTOCENE ASH BED, NEAR AMBERLEY, SOUTH ISLAND, NEW ZEALAND.

Introduction

A 4-8 cm thick white rhyolitic ash layer located 1 km north of the mouth of the Waipara River, Lat. 43°82'S; Long. 172°47.9'E (near Amberley, South Island, New Zealand, Figs 9, 10) was described and named Tiromoana ash by Carr (1970). The ash layer does not extend for more than 100 m continuously. Carr (1970) considered that the ash was preserved by colluvium (loess) at this locality and was not preserved anywhere else on the coastal plain because there was little or no sediment accumulating at other sites. The colluvium containing the ash was inferred by Carr (1970) to be Oturian - early Otiran in age (see Table 11). The age range of the ash was therefore considered to be probably older than 44,000 yr B.P. (the age of the oldest more widespread late Pleistocene rhyolitic tephra described by Vucetich and Pullar 1969) and younger than 270,000 yr B.P. (the age of the youngest rhyolitic ash preserved in deep-sea cores taken east of New Zealand, described by Ninkovich 1968).

A sample of the Tiromoana ash was received for identification from Mr. G. Warren, N.Z. Geological Survey, Christchurch, because the general age relationship indicated that it may correlate with central North Island rhyolite tephras. Subsequently the author accompanied by Messrs. C.G. Vucetich and R. Howorth visited the Amberley site, examined the stratigraphic context of the Tiromoana ash and collected further ash samples.

At the sampling site the fine-grained unbedded ash, 4-8 cm thick, was found to contrast in colour with olive-brown, massive, fine sandy sediment of similar particle size to the ash. The lower contact is sharp and the upper contact is gradational over 1-3 cm (Fig 11). Because the sediments containing the ash stand in massive columnar form (Fig 12) and have the particle-size character of undated loess deposits identified elsewhere within the Amberley area, they are considered to be loess. Subsequent fieldwork has failed to reveal

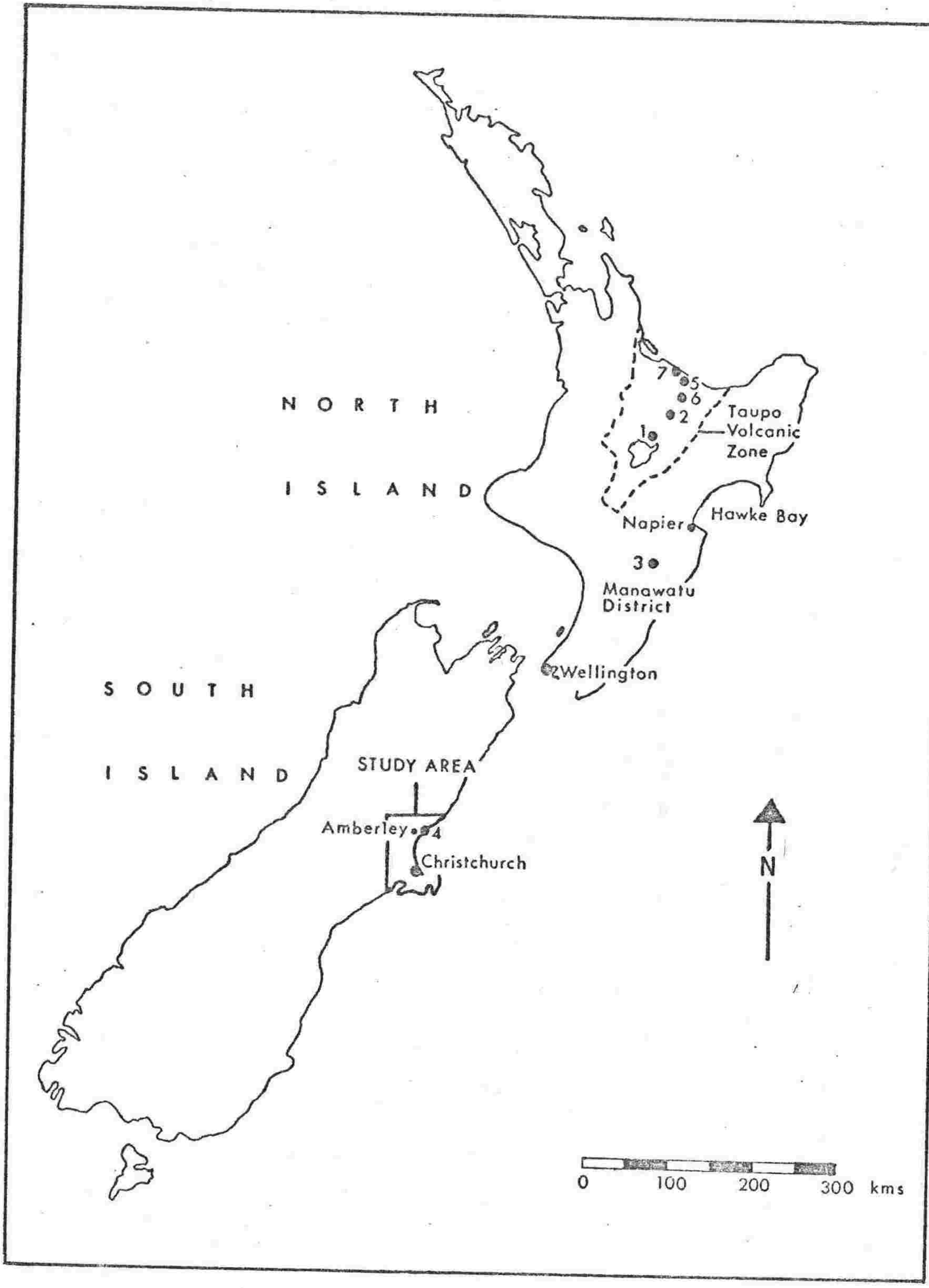

Fig. 9. - Map showing location of Amberley and study area. Numbers refer to location of sampling sites for tephra from which titanomagnetite has been extracted and analysed in this study (see Table 14).

STAGES OF COOLING AND COLD		STAGES OF WARMING AND WARMTH	
(New Zealand)	(United States)	(New Zealand)	(United States)
		Aranuian	Holocene
Otiran	Wisconsin		
		Oturian	Sangamonian
Waimean	Illinoian		
		Terangian	Yarmouthian
Waimaungan	Kansan		

Table 11. - Late Quaternary stages: New Zealand and Central United States.

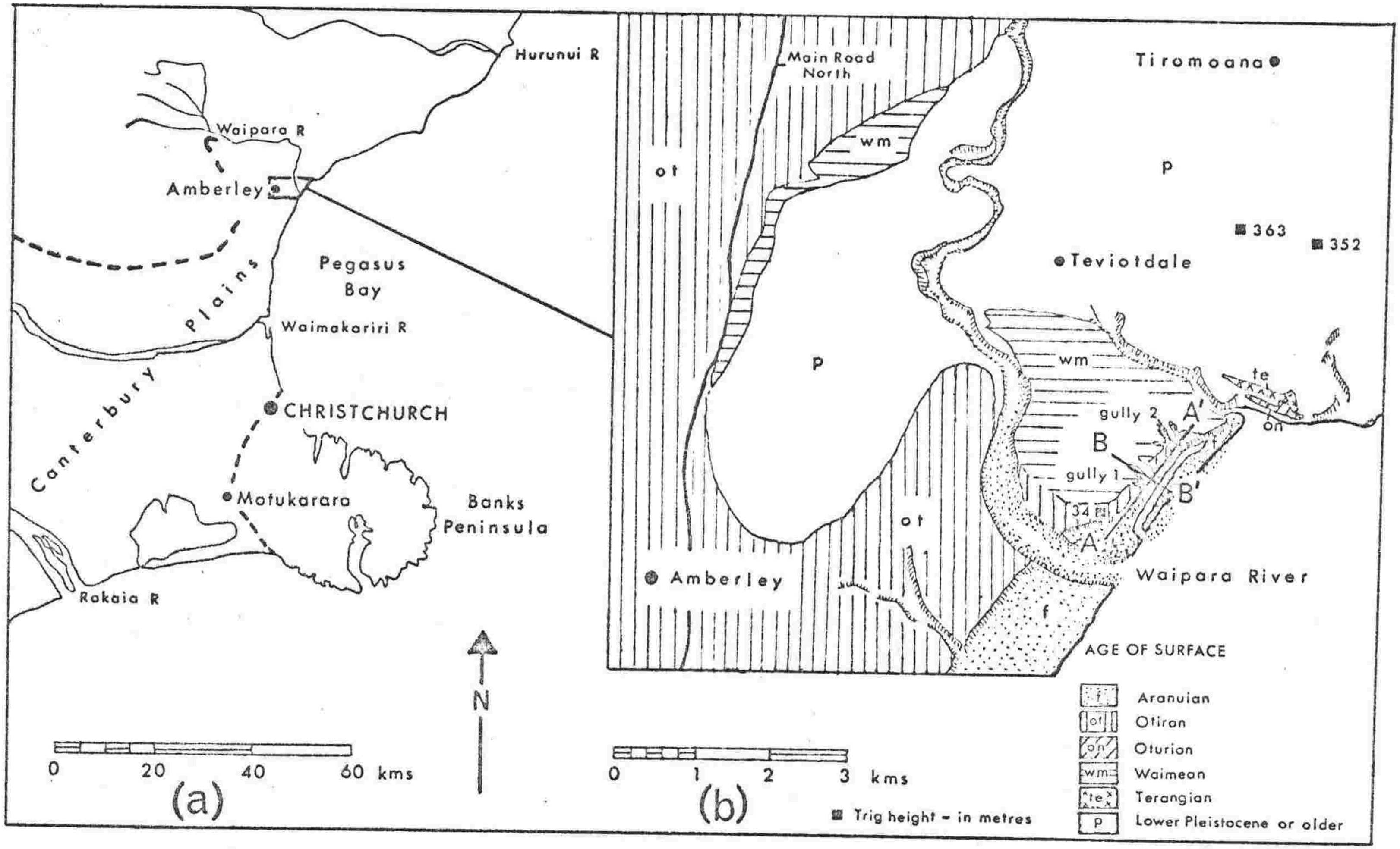

Fig. 10. - (a). Map showing area in which loess sections were examined for tephra-layers.
(b). Geological sketch map of Teviotdale area. Sections along lines A-A' and B-B' are shown in Fig. 13.

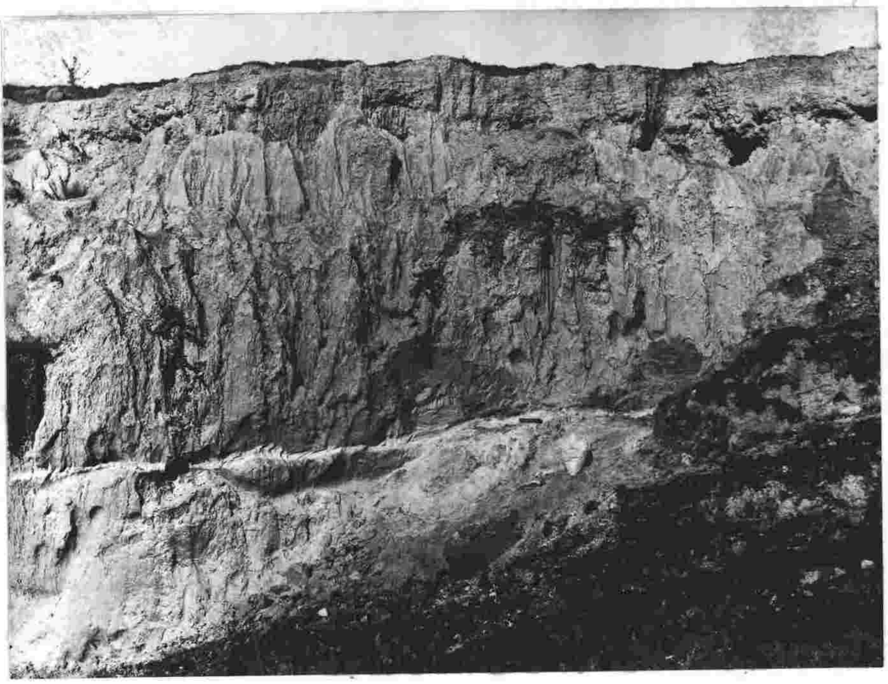

Fig. 11. - Oruanui Ash enclosed by loess 2 in Gully 1 (S68/154033 - 1964) at Teviotdale. The ash is 4-8 cm thick and has a sharp lower contact and a diffuse upper contact. Pen-knife is 10 cm long.

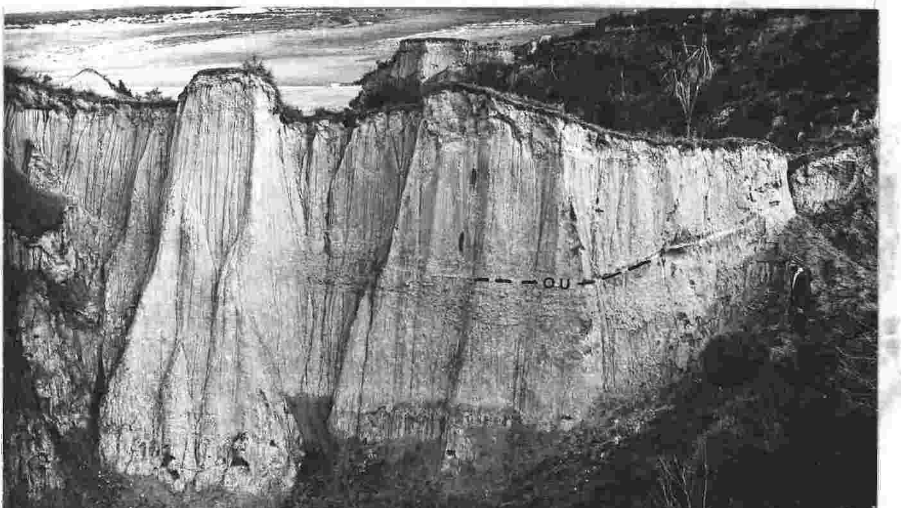

Fig. 12. - Loess 2 enclosing Oruanui Ash (ou) in Gully 2 at Teviotdale. Photograph taken, looking southwards across Pegasus Bay, shows Post-glacial marine cliff (upper middle) and Post-glacial transgressed surface (upper left).

Tiromoana ash elsewhere within the study area (Fig 10), despite the presence of thick deposits of undated greywacke-source loess (Birrell and Packard 1953, Raeside 1969 and N.Z. Soil Bureau Bulletin 27, 1968). The dating of Tiromoana ash at Amberley would allow correlation of the enclosing loess deposits over a wide area. Therefore studies on the ash included application of several correlation techniques and detailed examination of the depositional sequence.

Age and Identification of the Ash

The ash comprises about 90% glass shards, 9% terrigenous material (including quartz) and approximately 1% plagioclase and heavy minerals. The glass shards have a refractive index of 1.499 and generally range in size from 0.05-0.15 mm with a maximum of 0.25 mm. The rhyolitic nature of the glass is confirmed by its chemistry (Table 12).

The recent development of the fission-track method (Fleischer and Price 1964a) offers the geologist a new inexpensive tool for dating minerals and glasses. This dating method was therefore used to try and determine the age of glass shards from the Tiromoana ash.

Fission Track Dating: The technique used for fission-track age determinations is described on p. 164.

The fission-track age determined from glass shards of Tiromoana ash required approximately 60 man-hours. The longer than usual time taken for the age determination was required because of the relative youthfulness of the ash and low concentration of uranium in the glass. Although 2.92 cm^2 of glass surface was scanned for spontaneous fission tracks, accuracy and precision would have been improved if a larger area of glass had been examined. But it was necessary to make some concession to the accuracy required in order to spare the extra time and trouble involved.

The age of glass shards in the Tiromoana ash is 24,000 ± 8,900 yr B.P. (Table 13). This falls within the age range of late Pleistocene tephras erupted from the Taupo Volcanic

SiO_2	74.09
Al_2O_3	11.75
*Fe_2O_3	1.27
MgO	0.13
CaO	1.11
Na_2O	4.28
K_2O	2.95
TiO_2	0.12
P_2O_5	0.02
MnO	0.07
**Loss	4.81
TOTAL	100.60

* Total Fe as Fe_2O_3.
** Loss on ignition between 110°-1,000°C.

Table 12. - Chemical analysis of glass shards from Tiromoana ash. All elements except Na_2O were analysed by x-ray fluorescence using the method of Norrish and Hutton (1969). Na_2O was analysed by atomic absorption spectrophotometry.

SAMPLE NO.	ETCH TIME (secs.)	AREA SURVEYED (cm^2)	SPONTANEOUS FISSION TRACKS COUNTED	*INDUCED TRACK DENSITY (Track/cm^2)	FISSION-TRACK AGE (YR)
**11879	8	2.92	12	12,750 (± 2.6%)	24,000 ± 8,900

*For a neutron dose of 1.22×10^{15} (± 6%) (neutron density x velocity x time).
Decay constant for ^{238}U fission $\lambda_f = 6.85 \times 10^{-17}\ yr^{-1}$.

**Sample is housed in the petrological collection of the Geology Department, Victoria University.

Table 13. - Fission-track data and age of glass shards from Tiromoana ash.

Zone (Fig 1) described by Vucetich and Pullar (1969). Three of these tephras were widespread enough and fall into the general age range to possibly correlate with Tiromoana ash. These are Oruanui Ash, Mangaone Lapilli Formation member (c) and Rotoehu Ash of the Rotoiti Breccia Formation. Radiocarbon ages for these tephras are given in Table 2. Oruanui Ash has been identified near Wellington (Fig 9) by Vucetich and Pullar (1969) and this ash was provisionally correlated with Aokautere Ash (Cowie 1964 and Rhea 1968) which is widespread in the southern North Island. The most southerly localities that Mangaone Lapilli Formation member (c) and Rotoehu Ash have been found at, are at Napier (Fig 9) and in off-shore cores some 190 km SE of Napier (see p. 55).

The ferromagnesian assemblage of the Tiromoana ash was examined with particular note being taken of phenocrysts with attached glass (likely to be non-contaminants). The assemblage contains hypersthene + calcic-hornblende + traces of augite which is similar to that of Oruanui Ash and Mangaone Lapilli Formation member (c) (Table 3), but different from that of Rotoehu Ash which comprises mainly cummingtonite with lesser amounts of hypersthene and minor calcic-hornblende (Table 3).

The ^{14}C age range of Oruanui Ash is similar to the fission-track date for ash at Teviotdale, and together with the widespread extent and ferromagnesian assemblage of the former, it is probable that the two ashes are correlatives.

It has previously been shown (Kohn 1970, and Table 6) that most widespread rhyolitic tephras erupted from Taupo Volcanic Zone over the last 44,000 yr B.P. can be identified by the distinctive composition of their titanomagnetites. Thus, having shown the age limits of Tiromoana ash, a study of its titanomagnetite was undertaken to try and confirm correlation with Oruanui Ash.

Titanomagnetite Analysis: Initially, a bulk sample of titanomagnetite from Tiromoana ash was analysed by optical emission spectroscopy (Table 14, No. 1). When compared with titanomagnetite analysed from the three rhyolitic tephras which are possible correlatives (Table 14, Nos. 3-5), the analysis of titanomagnetite from Tiromoana ash shows higher Cr, Co and Ni, thus indicating a more basic composition. Quartz is present in some rhyolitic ashes in the central North Island. But the relatively high amount of quartz (and terrigenous material) is considered to be high for a tephra some 565 km from source. Thus, there may have been some post-depositional contamination of the ash (probably from enclosing loess). The basic nature of titanomagnetite from the enclosing loess (Table 14, No. 2) further indicates contamination of the Tiromoana ash, thus invalidating any correlations made by bulk titanomagnetite analysis.

In order to look for contaminants, homogeneous titanomagnetite grains (both discrete and enclosed by glass and orthopyroxene) were extracted from Tiromoana ash, and Oruanui Ash (from three localities) and analysed by electron microprobe (by Mr P.R. Kyle, Victoria University). Results are presented in Table 14 (Nos. 6 and 7). The microprobe analyses show that the titanomagnetite composition of the average (± 1 s.d.) of 10 analyses of Oruanui Ash (Table 15) is almost identical to the average (± 1 s.d.) of 13 analyses of titanomagnetite from Tiromoana ash. These analyses differ from titanomagnetites from pumices of Rotoiti Breccia Formation and Mangaone Lapilli Formation member (c) (analysed by both electron microprobe and optical emission spectroscopy - Table 14, Nos. 4, 5, 8 and 9) which have distinctly lower Ti, V and Cr and higher Mn contents. Titanomagnetites taken from tephra and analysed by optical emission spectroscopy may be compared with those analysed by electron microprobe for most elements (Table 14). But a valid comparison of Si, Al and Mg from bulk samples is not possible because of difficulties in removing impurities such as glass and orthopyroxene.

In order to test homogeneity of grains and range of elemental levels, electron microprobe scans covering 50-200 microns across grains for Ti, Mg and Cr were carried out on 64 grains of Oruanui Ash titanomagnetite and 70 grains of Tiromoana ash titanomagnetite.

Table 14. - Analyses of titanomagnetites from Tiromoana ash, loess enclosing the ash, Oruanui Ash, Mangaone Lapilli Formation, member (c), and Rotoiti Breccia Formation. Locality numbers refer to numbers in Fig. 9.

*Numbers prefixed by "P" belong to the petrological collection of the New Zealand Geological Survey. Numbers with no prefix belong to the petrological collection of the Geology Department, Victoria University (see Appendix II for details of sample localities).

Sample Nos. 1-5 were analysed by optical emission spectroscopy using procedure and operating conditions described by Kohn (1970).

Sample Nos. 6-7 and 10-11 were analysed by Mr. P.R. Kyle on the electron microprobe analyser of the Geology Department, Otago University; using procedures and conditions described by Kushiro and Nakamura (1970) with the exception of specimen beam current which was 0.02 A.

Sample No. 8 is a previously published analysis (Ewart *et al* 1971).

Sample No. 9 was analysed by Dr. C.P. Wood with the electron microprobe analyser of the N.Z. Geological Survey using procedure and conditions described by Carmichael (1967).

-; not determined.

OPTICAL EMISSION SPECTROGRAPHIC ANALYSES

SAMPLE NO.	1	2	3	4	5
%					
TiO_2	9.91	12.74	10.13	8.48	7.39
Al_2O_3	2.51	3.71	-	-	-
MgO	1.51	2.43	1.31	1.45	1.09
MnO	0.51	0.58	0.63	0.95	0.84
ppm					
V	3910	3261	3046	1179	2309
Cr	665	4095	427	20	81
Co	135	770	84	41	62
Ni	310	1590	102	24	57
Zr	140	165	124	692	430
Cu	-	-	34	20	22

ELECTRON MICRO-PROBE ANALYSES

	6	7	8	9	10	11
%						
SiO_2	0.04 ± 0.02	0.06 ± 0.02	0.04	0.06	0.08	0.07
TiO_2	10.21 ± 0.73	10.01 ± 0.75	7.60	8.59	9.44	9.42
Al_2O_3	1.57 ± 0.06	1.60 ± 0.08	1.37	2.09	3.35	3.12
V_2O_3	0.44 ± 0.20	0.30 ± 0.13	0.32	0.05	1.01	0.68
Cr_2O_3	-	-	0.03	0.02	0.05	0.06
FeO	82.08 ± 0.61	81.62 ± 0.89	83.76	81.88	79.03	79.01
MnO	0.57 ± 0.06	0.56 ± 0.09	0.79	1.04	0.30	0.31
MgO	0.66 ± 0.07	0.69 ± 0.08	0.74	0.76	2.74	3.00
ZnO	-	-	0.09	0.10	-	-
Sum	95.57	94.84	94.74	94.59	96.00	95.70
Recalculated analysis (Ulvospinel Basis)						
Fe_2O_3	47.54	47.47	52.64	49.84	47.54	48.16
FeO	39.28	38.96	36.40	37.03	36.25	35.67
Total	100.31	99.65	100.01	99.58	100.76	100.52

KEY TO SAMPLE NOS.

1. *11879, Tiromoana ash (locality 4).
2. Loess enclosing Tiromoana ash (locality 4).
3. 11877 Oruanui Ash, 181-264 cm above base - chalazoidites (locality 1).
4. 11892 Mangaone Lapilli Formation member (c), basal 30 cm (locality 5).
5. Rotoehu Ash of the Rotoiti Breccia Formation, basal 20 cm (locality 6).
6. Average (± 1 s.d.) for 3 samples of Oruanui Ash (from localities 1 [11877], 2 and 3 - 10 analyses).
7. " " " 2 " " Tiromoana ash (from locality 4 - 13 analyses).
8. P30411 - phenocryst Rotoiti Breccia Formation (locality 7).
9. 11892 - phenocryst Mangaone Lapilli Formation member (c) (locality 5).
10. 11877 - xenocryst in Oruanui Ash (locality 1).
11. 11879 - xenocryst in Tiromoana ash (locality 4).

\- not determined.

Approximately 85% of all the titanomagnetites scanned are chemically similar. Averaged analyses of these grains (Table 14; No. 6 - average of 10 analyses and No. 7 - average of 13 analyses) show relatively large standard deviations for titanium iron and vanadium. This titanomagnetite is considered to be typical of Oruanui Ash.

Approximately 5% of the grains scanned were exsolved. The remaining 10% comprised grains which were more basic in composition than the typical grains. Analyses of these basic grains in Oruanui Ash and Tiromoana ash are given in Table 14 (Nos. 9 and 10). These homogeneous, basic grains are considered to be xenocrysts, which were incorporated in the Oruanui Ash during its eruption. Scans of a small number of xenocrystic titanomagnetite grains from Tiromoana Ash show higher Ti, Mg and Cr. Since grains of this composition do not occur in Oruanui Ash they are considered to be local contaminants, and their presence explains the high Cr, Co and Ni values in the bulk analysis (Table 14, No. 1).

On the basis of the rhyolitic nature of the glass, the fission-track date of the glass, ferromagnesian assemblage and electron-microprobe analyses of titanomagnetites, Tiromoana ash at Teviotdale is almost certainly the c. 20,000 yr B.P. Oruanui Ash.

The Depositional Sequence at Teviotdale

The following stratigraphic column is described from the sampling site for Tiromoana ash in Gully 1 (Fig 10).

STRATIGRAPHIC COLUMN - GULLY 1 TEVIOTDALE

(A)	0.15 m	dark brown silt loam, friable, moderately developed granular and crumb structure; indistinct lower boundary,
(B1)	0.10 m	brown (10 YR 5/3) silt loam, friable and firm, weakly developed granular and crumb structure, few fine strong brown mottles; distinct lower boundary,
(B2)	0.20 m	brown (10 YR 5/3) fine, sandy clay loam; varicoloured with fine to coarse distinct 7.5 YR 5/4 and 4/6 mottles, very firm, strongly developed blocky structure, distinct lower boundary,
(C1)	0.25 m	olive brown sandy loam (2.5 YR 5/4), (LOESS 2), firm, massive merging to less massive fine sandy loam, indistinct lower boundary,
(C2)	4.20 m	olive brown fine sandy loam (LOESS 2); massive, weakly developed fragmental blocky structure, white $CaCO_3$ flecks throughout and increasing with depth, indistinct regular boundary,
	0.07 m	white ash, massive, non-banded, with upper half very lightly stained olive brown, lower contact is sharp but with amplitude of 0.5 cm Tiromoana ash.
	1.50 m	olive brown fine sandy loam (LOESS 2), distinct boundary,
	0.25 m	greywacke gravels, subrounded, moderately weathered, distinct boundary,
	4.52 m	olive brown, fine sandy loam (LOESS 2), for gravel lenses 10-50 cm thick,
	0.15 m	olive yellow sands,
	0.05 m	olive brown fine sandy loam, flecked dark brown, massive (weakly developed paleosol), distinct lower boundary,
	1.0 m	olive brown sandy loam, (LOESS 1), faint brown mottling, pale, distinct lower boundary,

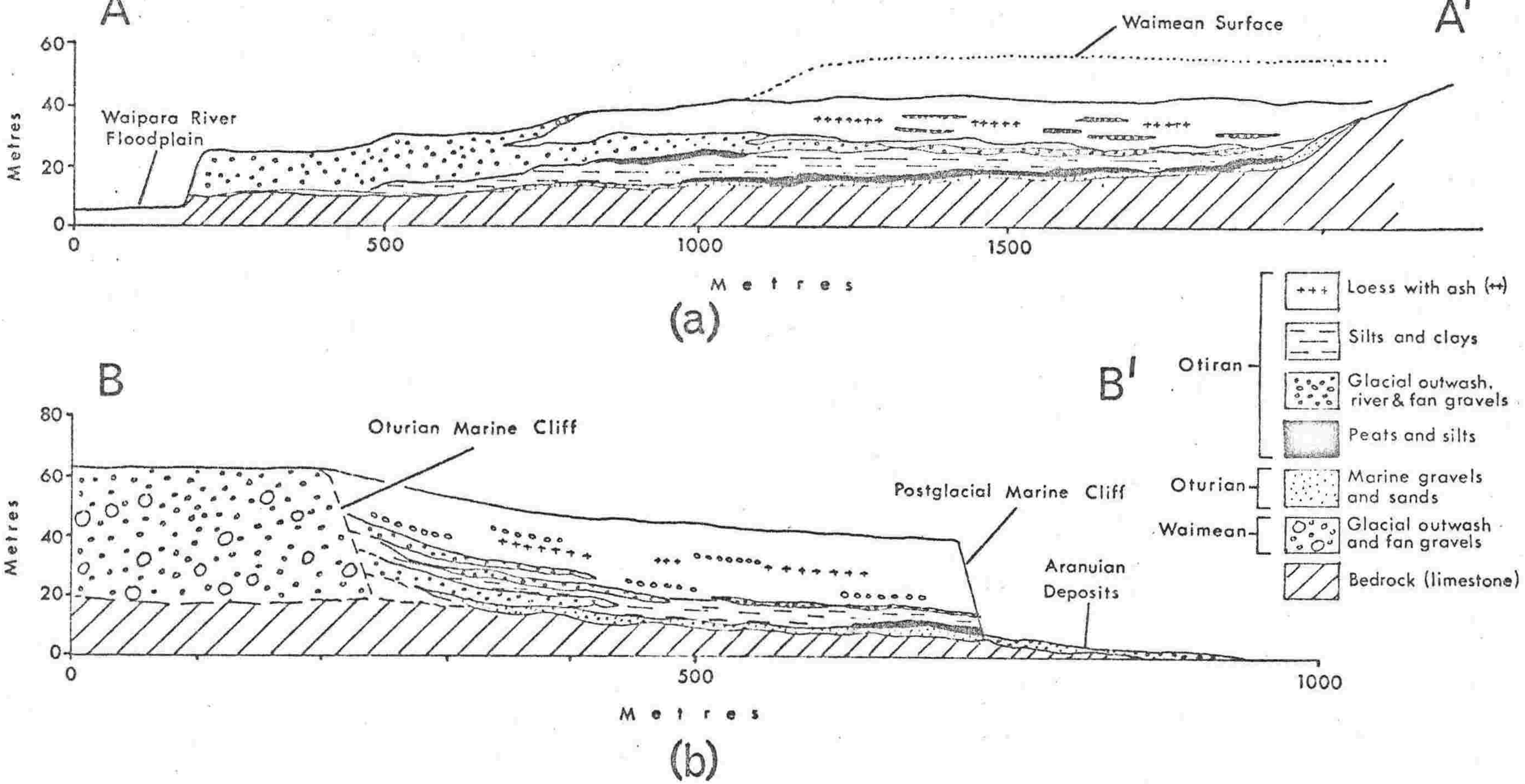

Fig. 13. - (a). Longitudinal section A-A' along Post-glacial marine cliffs, Teviotdale, South Island.
(b). Cross section B-B' from Waimean surface to Post-glacial transgressed surface, Teviotdale.

1.0 m	olive brown silty clay, blocky structure, weak paleosol character, distinct boundary,
2.0 m	greywacke gravels, subrounded, weakly-moderately weathered,
3.0 m	olive silty clays, blocky, weakly banded, strong paleosol character, diffuse lower boundary,
2.0 m	multiple bedded silty clays, olive with many prominent 0.20 cm thick lignite bands, sharp lower contact,
2.0 m	at least, pebble sands, weakly indurated, slightly cemented (Oturian marine sands),
——	major unconformity marks marine benching on Miocene shelly limestones.

The section described at the sampling site for Tiromoana ash in gully 1 is illustrated in Fig 13 b. The sequence of beds in longitudinal section Fig 13 a,varies from the gully 1 section mainly in the lensing of basal finely banded silty clays with lignite bands, and the presence of gravel stringers in the upper part of the section. The gravel stringers thicken to the NW (Fig 13 b) and this clearly shows the form of these colluvium fans. The source of the gravels is the appreciably thick outwash gravels (Waimean) cliffed during the presumed Last Interglacial high sea level; the source of the fine silty and silty clay sediments is partly colluvial and partly primarily ~~aolean~~ aeolian material (loess). The source of the upper fine grained sediment, previously established to be loess, is to the westward and to windward. Preservation of the ash at Teviotdale is attributed to special site conditions to leeward of the Waimean terrace (lacking loess cover) from which the ash was redistributed and concentrated, and rapidly covered by loess.

Discussion

The 20,000 yr B.P. Oruanui Ash provides a major time plane in proving the depositional sequence in the many gully sections exposed at Teviotdale. The ash provides the means to apportion time to deposition and soil development within the sequence. The base of the post-Waimean depositional sequence at Teviotdale relates to pebbles and sands exposed following the Oturian transgression at c. 80,000 yr B.P. Accordingly at the section (Gully 1) the 5 m thickness of sediments above the ash is assigned to a 20,000 yr period and the 11 m thickness below the ash is assigned to a c. 60,000 yr period.

The preservation of Oruanui Ash within Loess 2 declares a late Otiran loess period for which about two-thirds of the loess thickness is below the ash and one third above. The relative thickness of the two loess beds each of similar morphology is not thought to imply corresponding periods of accumulation. The onset of the loess phase is linked with the Kumara Glacial Advance 2.1 (23,000 yr B.P.) and the close of the loess period with the later Kumara Glacial Advance 3 (14,000 yr B.P.) (Suggate and Moar, 1965). It is also linked with the Ohakea loess of Manawatu c. 25,000 to 12,000 yr B.P. (D. Milne, pers. comm.); the Late Otiran accelerated erosion c. 24,000 to 22,500 yr B.P. of the Taupo Volcanic Zone (Vucetich 1973), and subsequent deposition of "tephric-loess" with high glass content, between the ^{14}C dated Oruanui Ash (c. 20,000 yr B.P.) and Rerewhakaaitu Ash (c. 14,700 yr B.P.) (Vucetich and Pullar 1969).

Non-calcareous - Loess 1, with a weakly developed paleosol, is thought to be older than 35,000 yr B.P. and is thus a probable correlative of Tini Loess (Fleming 1972); it is also probably related to the 37,000 yr B.P. stadial of Brodie (1957). The significance of a 15 cm thick lense of well sorted (?beach) sand at the upper contact of the paleosol is not known.

In the lower part of the section, the presence of peats, together with the strong paleopedogenic character of the silts and clays, and the absence of gravel stringers, implies a period of slow accumulation during an interstadial.

The ash at Teviotdale is the only known occurrence to date of Oruanui Ash in South Island. As the Oruanui Ash identifies late Otiran loess at Teviotdale, similar loess deposits without ash-layers, in the study area can now be dated. A further important role of Oruanui Ash at Teviotdale is in strengthening correlations of late Otiran deposits between the North Island and Canterbury.

4. RELATION OF THE EARTHQUAKE FLAT BRECCIA TO THE ROTOITI BRECCIA, CENTRAL NORTH ISLAND, NEW ZEALAND.

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RELATION OF THE EARTHQUAKE FLAT BRECCIA
TO THE ROTOITI BRECCIA,
CENTRAL NORTH ISLAND, NEW ZEALAND.

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ABSTRACT

Tephra correlations demonstrate that the rhyolitic pyroclastic flow and airfall deposits of the Earthquake Flat Breccia Formation were erupted immediately following the eruption of the Rotoiti Breccia Formation at radiocarbon date 41,700 ± 3,500 yrs B.P. (NZ1126). The two eruptive centres were 26 km apart. A widespread airfall tephra accompanying the eruption of the Earthquake Flat Breccia has previously been regarded as part of the Rotoehu Ash component of the Rotoiti Breccia Formation.

All the field correlations are confirmed and others are directly established by the distinctive chemical content of titanomagnetites in the pyroclastic deposits studied.

INTRODUCTION

The Earthquake Flat Breccia Formation (Healy <u>et al</u>, 1964) is a thick, unwelded, biotite-rich, rhyolitic ash and pumice deposit, covering 110 km^2 surrounding Earthquake Flat (Fig 1). The formation consists of many pyroclastic flow units with inter-

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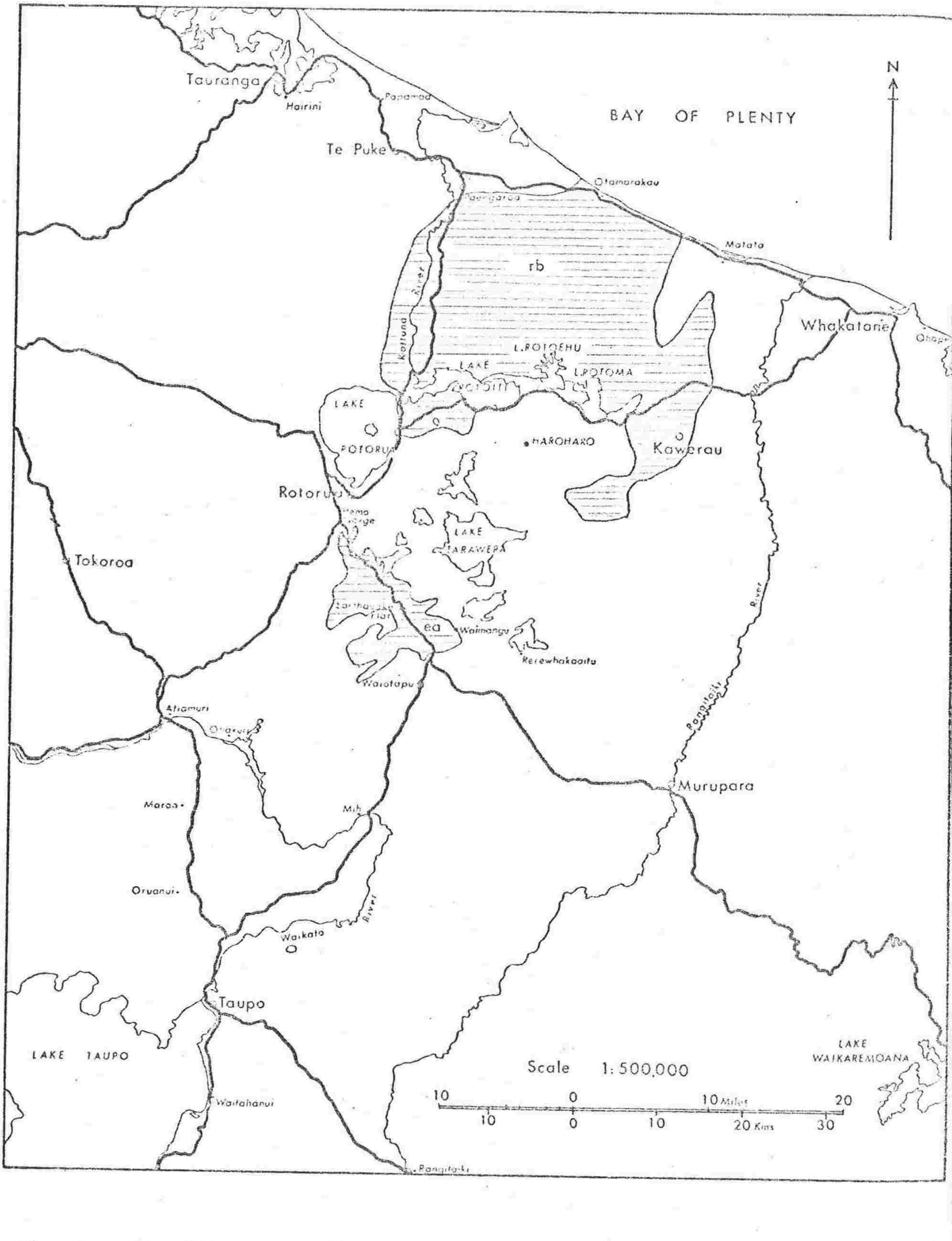

Fig. 1. - Locality map of Taupo-Rotorua-Bay of Plenty region, and distribution of Earthquake Flat Breccia (ea) and Rotoiti Breccia (rb) pyroclastic-flow deposits.

bedded and mantling airfall pyroclastic units, erupted from a 5 km line of explosion craters, of which Earthquake Flat is the largest.

Ages proposed for the Earthquake Flat Breccia are: Grindley (1959) less than 50,000 years, and Thompson (1968a) about 20,000 years.

The Earthquake Flat Breccia deposits have been considerably faulted and have also undergone considerable erosion. The date of deposition is thus important in determining rates of faulting and erosion, as well as the position of the formation in the stratigraphic sequence of the Central Volcanic Region.

STRATIGRAPHY

The late Pleistocene tephras (airfall pyroclastics) of the central North Island have been described and mapped by Vucetich and Pullar (1969). Radiocarbon ages have been obtained for many of these tephras, and these now provide valuable time planes for the dating of other deposits.

The Mangaone Lapilli Formation and the Rotoehu Ash of the Rotoiti Breccia Formation (Vucetich and Pullar, 1969) are widespread tephra deposits, found critical for dating the Earthquake Flat Breccia Formation. The Mangaone Lapilli Formation comprises five members (a) to (e) in order of eruption (Vucetich and Pullar, 1969). Paleosols developed at the contacts between members indicate time intervals between the eruptions. Rotoehu Ash, underlying the Mangaone Lapilli Formation, is the widespread tephra associated with the Rotoiti Breccia pyroclastic flow eruptions (Vucetich and Pullar, 1969). It consists of airfall pyroclastic units which underlie, are interbedded with, and mantle the Rotoiti Breccia flow deposits (Nairn, 1972). The Rotoiti Breccia Formation (Rotoiti Breccia and Rotoehu Ash) is considered to have been erupted from Haroharo Rhyolite Complex (**Fig 1**) some 26 km north-east of Earthquake Flat.

Vucetich and Pullar (1969, p. 813) were unable to fully establish the relationship of the late Pleistocene tephra column to the Earthquake Flat Breccia, but the Mangaone Lapilli (member unspecified) was found overlying the breccia with apparent unconformable contact.

In recent examination of preserved original surfaces of the Earthquake Flat Breccia fans, several sections were found where Mangaone Lapilli member (a) conformably overlies moderately developed paleosols on the mantling tephra unit of the Earthquake Flat Breccia. An example of such a section at Tumunui Road is shown in **Fig 2.** Rotoehu Ash was not found in these conformably mantling sequences, although it is present at higher elevations on Kakapiko rhyolite dome (N76/744953), and at Maleme Road (N85/598781) near Ohakuri (see **Fig 1**). At Haumi Stream - Waimangu (N85/869857), a rare exposure of the base of the Earthquake Flat Breccia shows it to overlie a 7 m thick pisolitic breccia without a weathering or erosional break at the contact. The pisolitic breccia is enclosed within shower-bedded pyroclastic units similar to, and here correlated with, the basal and mantling tephra units of the Rotoiti Breccia Formation - units which largely comprise the Rotoehu Ash. Furthermore, in the Rotorua area, cummingtonite has been found only in deposits erupted from Okataina Volcanic Centre and is the distinctive mineral of the Rotoiti Breccia (Ewart, 1968, p. 528). Cummingtonite was identified by X-ray diffraction analysis of heavy mineral separates from the pisolitic breccia. The lack of an erosional or weathering break between the Earthquake Flat Breccia and the underlying pisolitic breccia (Rotoiti Breccia), indicates that no significant time interval separated the Earthquake Flat and Rotoiti eruptions.

A similar relationship between Rotoehu Ash and the Earthquake Flat Breccia has been recently exposed in a more accessible section 4 km south of the Hemo Gorge on the Taupo-Rotorua Highway (N76/727959, Fig 3). The section is described as:-

Rotorua Sub-group	3 m	brown ash (Holocene).
		eroded top.
Earthquake Flat Breccia	3 m	ash and lapilli flow unit, containing abundant biotite.
	0.3 m	shower-bedded coarse ash - airfall tephra unit.
	0.3 m	grey fine ash.
		sharp, unweathered contact.
	0.15 m	shower-bedded grey medium ash.
	3 m	poorly stratified, pisolitic yellow fine ash.
	0.3 m	shower-bedded coarse ash and lapilli.
Rotoehu Ash	0.25 m	shower-bedded grey ash.
	0.15 m	finely bedded ash.
	50 mm	brown coarse ash.
	30 mm	cream fine ash
	70 mm	grey medium ash.
		sharp contact.
Breccia associated with Kakapiko rhyolite dome	1 m	carbonaceous paleosol on exposed ash and block flow unit.
		Base of section

Fig. 2. - Mangaone Lapilli member (a) [Mn (a)] conformably overlying paleosol (pal) developed on mantling tephra unit of Earthquake Flat Breccia Formation, Tumunui Road (N85/722887).

Fig. 3. - Earthquake Flat Breccia (ea) overlying Rotoehu Ash (Re) without time break. Taupo-Rotorua Highway, 4 km south of Hemo Gorge (N76/727959).

CHRONOLOGY

The Mangaone Lapilli Formation member (c) has been radiocarbon dated at 30,100 ± 1,300 years B.P. (NZ868, T.L. Grant-Taylor pers. comm., Pullar and Heine, 1971). Paleosols developed on underlying members (a) and (b) indicate that member (a) is somewhat older than this date. The Rotoiti Breccia Formation has been dated at >41,000 years B.P. (67% probability, NZ643, Thompson, 1968b) and at 44,200 ± 4,300 years B.P. (67% probability, NZ877, Grant-Taylor and Rafter, 1971). No time breaks are present within the Rotoiti Breccia Formation (Nairn, 1972) and the radiocarbon ages also date the widespread Rotoehu Ash.

A wood sample taken from the paleosol beneath the basal tephra of the pisolitic breccia at Haumi Stream gave a radiocarbon age of 41,700 ± 3,500 years B.P. (NZ1126 T.L. Grant-Taylor, pers. comm.). The similarity of this age to those already obtained for the Rotoiti Breccia is further evidence for its correlation with the pisolitic breccia. As no erosional or weathering break occurs at the upper contact of the pisolitic breccia, the radiocarbon age also dates the overlying Earthquake Flat Breccia deposits.

WIDESPREAD AIRFALL COMPONENT

Shower-bedded tephra units, which are intercalated within and mantle the Earthquake Flat Breccia flow deposits, have a widespread distribution beyond the limits of the flow breccia and provide an independent check of the stratigraphic relationship between the Earthquake Flat Breccia and Rotoiti Breccia formations.

Shower-bedded Rotoehu Ash at Maleme Road (N85/598781), 21 km south-west of Earthquake Flat, is overlain by 0.9 m of pinkish-grey ash (Fig 4) containing abundant biotite - the distinctive mineral of the Earthquake Flat Breccia Formation. The contact between the two deposits is sharp, without erosional or weathering break. The biotite-rich upper ash is here correlated with tephra units of the Earthquake Flat Breccia Formation, although previously regarded as part of the Rotoehu Ash (Vucetich and Pullar, 1969, p. 791, - Fig 4). This correlation is supported by X-ray diffraction analysis of heavy mineral separates from the biotite-rich ash, which has an identical composition to samples from the Earthquake Flat Breccia flow deposits, and differs from Rotoehu ash in the absence of cummingtonite. Biotite-rich tephra overlies shower-bedded Rotoehu Ash in further sections at Butcher Road (N85/751669) near Mihi (see Fig 1), and at Murupara (N86/125658). Again no weathering or erosional break is apparent between the beds at these sections. The name "Rifle Range ash" is informally used for the biotite-rich tephra, a name taken from the northernmost crater in the Earthquake Flat Breccia source area, where thick mantling airfall pyroclastics are exposed.

IDENTIFICATION OF PYROCLASTIC DEPOSITS BY CHEMICAL ANALYSIS OF TITANOMAGNETITES

The use of chemical analysis of titanomagnetites as a rapid method of identification of Late Quaternary tephras from the Taupo Volcanic Zone, and thus as a check for field correlations, has been described by Kohn (1970). Titanomagnetites were separated from samples taken from member (a) of the Mangaone Lapilli Formation, and from pyroclastic airfall and flow units within the Earthquake Flat Breccia and Rotoiti Breccia

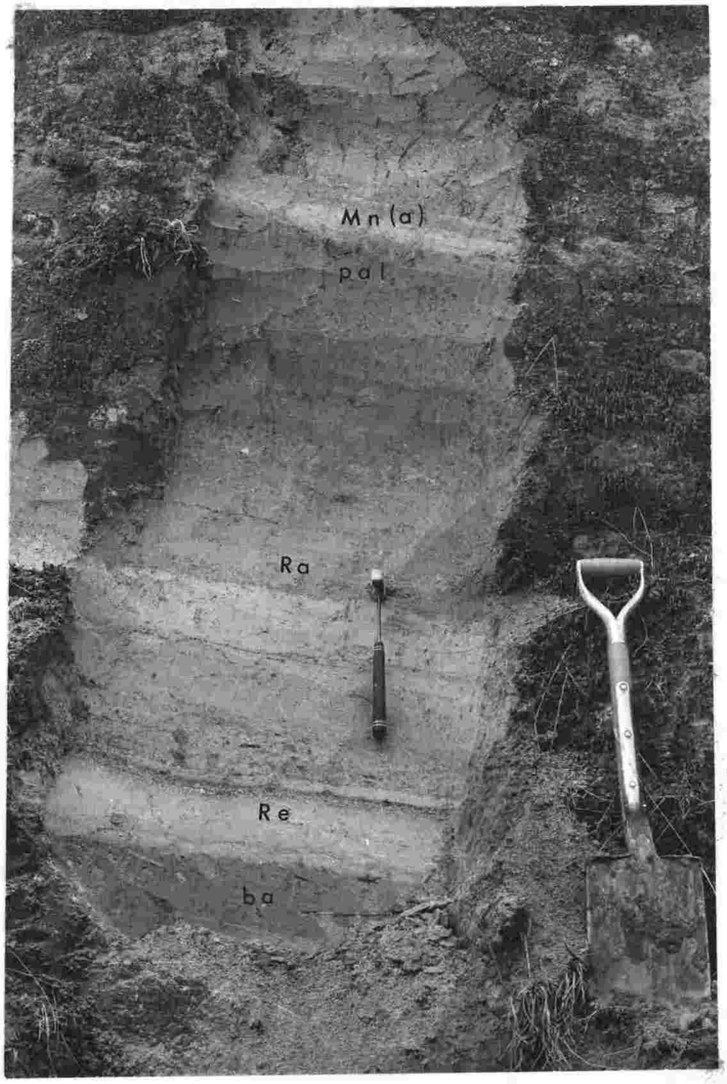

Fig. 4. - Tephra sequence at Maleme Road (N85/598781). Mangaone (a) [Mn (a)] overlies a paleosol (pal) developed on biotite-rich "Rifle Range ash" (Ra). Hammer head rests at contact of "Rifle Range ash" and Rotoehu Ash (Re), overlying brown ash beds (ba).

deposits. Samples were extracted by hand magnet and concentrates were purified by repeated magnetic separations under acetone. The titanomagnetite samples were then analysed by means of an optical emission spectrograph, using the methods described by Kohn (1970). The location of sample sites, and results of analyses are given in Table 1.

The results show that the composition of titanomagnetite does not vary greatly either vertically or laterally within any one formation, and that the shower-bedded airfall and unstratified pyroclastic flow units within any one formation have similar titanomagnetite compositions despite the different mechanisms of deposition. Analysis of titanomagnetite from the airfall unit mantling the Rotoiti Breccia at Paengaroa demonstrates a similar composition to that of the underlying Rotoiti Breccia deposits. This mantling airfall unit contains small amounts of biotite (Nairn, 1972), a mineral not previously described from the Rotoiti Breccia Formation (cf Ewart, 1968). Despite the change in mineralogy within this formation, the titanomagnetite composition remains unchanged.

Differences in the composition of the titanomagnetites of the three formations studied is shown in Table 1. The Mangaone (a) titanomagnetite has higher vanadium, chromium, cobalt and nickel contents and a lower manganese content than titanomagnetite from the other two formations. The Earthquake Flat Breccia titanomagnetite differs from that of the Rotoiti Breccia in having a higher chromium content (usually greater by a factor exceeding two), and a lower magnesium and manganese content. Calcium and zirconium are quite variable within the titanomagnetite of any one formation, this being due to minute apatite and zircon crystals which could not be removed in the purification process.

ROTOITI BRECCIA FORMATION

Sample No.(†)	Location	Grid Reference	Ti%	Mg%	Mn%	Ca%	V.	Cr	Co	Ni	Zr	Cu
15,018a	Saunder's Track, basal grey shower-bedded Rotoehu Ash at base of flow deposits	N67/818347	4.29	0.76	0.71	0.13	2395	75	60	56	143	15
15,020a	Saunder's Track, shower-bedded Rotoehu Ash 0.9 m from base of Rotoiti Breccia Formation	N67/818347	4.48	0.77	0.71	0.10	2468	84	77	59	74	14
15,022a	Malere Road, Rotoehu Ash under Rifle Range ash.	N85/598781	3.89	0.74	0.65	0.10	2269	63	74	61	612	17
	Kawerau Rubbish Dump, basal shower-bedded Rotoehu Ash of Rotoiti Breccia Formation	N77/160090	4.27	0.71	0.72	0.77	2578	67	76	72	311	27
	Waihi Beach, basal 0.2 m of Rotoehu Ash	N53/434880	4.06	0.73	0.69	0.11	2260	61	60	52	440	17
	Hairini, basal 0.15 m of Rotoehu Ash	N58/645548	4.08	0.65	0.59	0.11	2130	54	63	58	568	16
	Hairini, 0.97-1.15 m (from top), Rotoehu Ash	N58/645548	4.08	0.69	0.69	0.13	2301	59	61	56	579	18
	Hairini, 0.04-0.2 m (from top), Rotoehu Ash (in paleosol)	N58/645548	4.29	0.81	0.69	0.09	2431	76	88	74	357	27
	Waihua Beach, 0.74-0.9 m (from top), Rotoehu Ash	N115/689868	4.07	0.72	0.59	0.13	2261	63	81	58	77	14
	Matahina Road, basal 0.1 m, Rotoehu Ash	N86/055859	5.01	0.71	0.74	0.54	2435	73	59	44	499	29
	Braemar Road, 0.56-0.7 m (from top) Rotoehu Ash	N68/202265	4.43	0.66	0.65	0.14	2309	81	62	57	430	22
	Braemar Road, 0.03-0.18 m (from top), Rotoehu Ash (in paleosol).	N68/202265	4.41	0.73	0.61	0.13	2481	91	74	64	320	21
15,017a	William's Track, shower-bedded Rotoehu Ash overlying Rotoiti Breccia	N67/843353	4.44	0.75	0.69	0.09	2534	85	79	58	97	21
15,012	Saunder's Track, Rotoiti Breccia flow unit, 0.46 m above basal shower-bedded Rotoehu Ash.	N67/818347	3.93	0.69	0.74	0.09	2400	56	64	57	454	26
15,010	William's Track, 0.6-0.8 m from top of Rotoiti Breccia	N67/843353	4.22	0.75	0.65	0.14	2265	84	64	60	303	22
	Ormond's Quarry, Rotoiti Breccia	N76/854147	4.38	0.63	0.59	0.88	1908	57	57	40	530	33
	*Kawerau Rubbish Dump, Rotoiti Breccia	N77/160090	4.52	0.69	0.66	0.26	2056	55	54	44	408	27
15,014	*Whaka Forest, Rotoiti Breccia	N76/753003	4.42	0.70	0.69	0.42	2260	76	66	61	302	25
15,013	*Haumi Stream, "pisolitic breccia"	N85/869857	4.28	0.76	0.74	0.58	2245	77	68	60	147	21

BRECCIA FROM KAKAPIKO RHYOLITE DOME

Sample No.	Location	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
15,023	Whaka Forest, lookout drive, opposite Peka Gully, Kakapiko Rhyolite Breccia	N76/730950	5.10	0.52	0.69	0.11	2008	187	52	56	156	18
	MANGAONE LAPILLI FORMATION - MEMBER (a)											
	Matahina Road, basal pumice lapilli and blocks	N86/096874	4.68	0.73	0.38	0.18	3457	228	121	106	398	22
	Tumunui Road, pink ash	N76/733905	5.10	0.71	0.43	0.19	3590	255	104	116	439	27
	Braemar Road, basal 0.09 m of ash and lapilli	N68/202265	4.51	0.75	0.40	0.14	3522	271	97	110	280	19
	Braemar Road, 0.4–0.48 m (from top), pink ash	N68/202265	4.63	0.73	0.42	0.14	3531	241	88	106	323	21
	EARTHQUAKE FLAT BRECCIA FORMATION											
15,005/1	Rotorua-Taupo Highway, Earthquake Flat Breccia	N76/783903	5.70	0.55	0.59	0.49	2407	226	68	60	563	38
15,007/3a	Near Tumunui Road, airfall tephra, basal Earthquake Flat Breccia	N85/716891	4.59	0.60	0.58	0.52	2474	235	71	76	469	22
15,005/3a	Rotorua-Taupo Highway, airfall tephra overlying Earthquake Flat Breccia	N76/783903	5.97	0.58	0.54	0.27	2527	220	60	63	354	36
	*Rotorua-Murupara Highway, Rifle Range ash, 0.35-0.42 m.	N86/125658	5.44	0.48	0.68	0.12	2904	212	72	86	877	46
	*Rotorua-Murupara Highway, Rifle Range ash, 0.64–0.69 m.	N86/125658	5.04	0.49	0.73	0.12	2773	185	68	72	607	41
15,009a	*Maleme Road, Rifle Range ash	N85/598781	4.81	0.57	0.62	0.11	2501	177	67	63	1097	24
	*Butcher Road, Rifle Range ash.	N85/751669	6.07	0.47	0.56	0.03	2321	160	64	80	342	38
	*Waihua Beach, Rifle Range ash, top 0.08–0.18 cm (of Rotoehu Ash)	N115/689868	4.66	0.67	0.61	0.30	2421	166	73	71	205	25

<u>Table 1</u>. - Chemical analyses of titanomagnetites from the late Quaternary pyroclastic deposits studied (values are in ppm unless otherwise indicated). Analyses presented are the average composition of samples† which have generally been run in triplicate. The analytical precision, expressed as relative deviation, was approximately ± 10%.

† Numbers refer to samples in the Victoria University, Geology Department petrological collection.

* Correlatives proven by stratigraphy and titanomagnetite analysis.

Further samples were taken from the pisolitic breccia which underlies the Earthquake Flat Breccia at Haumi Stream, and from deposits of the proposed "Rifle Range ash" at Maleme Road, Butcher Road, and Murupara. Titanomagnetite analyses (Table 1) support the identification of "pisolitic breccia" as Rotoiti Breccia, and also the correlation of the Rifle Range ash deposits with the Earthquake Flat Breccia. A further chemical identification of Rifle Range ash was unexpectedly made in a sample from the top of Rotoehu Ash at Waihua Beach (N115/689868 - 14 km south-west of Wairoa, Hawkes Bay).

Titanomagnetite analysis also invariably confirmed the field identification of Mangaone Lapilli member (a).

DISTRIBUTION OF RIFLE RANGE ASH

The widespread nature of Rifle Range ash is demonstrated by its presence at Butcher Road, Maleme Road, Murupara, and Waihua, all localities where the field identifications have been confirmed by titanomagnetite analysis. Rifle Range ash is 0.6 m thick at Maleme Road and at least 0.68 m thick at Murupara, these sections being sited 21 km south-west and 35 km south-east of Earthquake Flat respectively; and is estimated at 0.3 m thick at Waihua Beach 120 km south-east from source. These sections indicate that the biotite-rich Rifle Range ash has a widespread, if previously unsuspected, distribution. The absence of Rifle Range ash in sections at Roydon Downs and Paengaroa, 48 km to north of Earthquake Flat, and from Hairini (near Tauranga, <u>see</u> Fig 1 and Table 1) 60 km north-west of source indicates a strongly directional fallout pattern to the south-east. This pattern is common to many other tephras erupted from the Taupo Volcanic Zone.

SUMMARY

The stratigraphic and chemical evidence demonstrates that the Earthquake Flat eruptions immediately followed those of the Rotoiti Breccia, at c. 42,000 years B.P. radiocarbon age. Widespread biotite-rich tephra showers (Rifle Range ash) accompanied the Earthquake Flat eruptions, and these have previously been regarded as part of the Rotoehu Ash. The fall-out pattern of the Rifle Range ash appears to be strongly directional to the south-east.

ACKNOWLEDGMENTS

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5. MISCELLANEOUS STUDIES

Vanadium Contents of Titanomagnetite from Kaharoa Tephra and Mangaone Lapilli

Titanomagnetites analysed from samples taken vertically through three sections (Fig 14) of multiple shower bedded Kaharoa Ash on Mt Tarawera (Nos.* 10-14), at Northern Boundary Rd, (Nos. 15-21) and Matahina Rd(Nos. 25, 26) show a general upward increase of V contents. The isopach map of Kaharoa Ash shows a northern and a south-eastern lobe (Vucetich and Pullar 1964) and it was largely on the basis of V content that Kohn (1970) showed that the titanomagnetite composition of the lobes was different. Beyond Murupara (Fig 1) on the axis of the south-eastern lobe, Kaharoa Ash loses its multiple shower-bedded nature and V content of titanomagnetites (Nos. 22, 23, 24, 27, 36) is invariably similar to those titanomagnetites sampled from basal tephra at near source sections sampled vertically. Titanomagnetite sampled from basal Kaharoa Ash at sites north of Mt Tarawera (Nos. 29, 31) contain V abundances similar to those of the middle and upper parts of Kaharoa Ash elsewhere.

The above data indicate that the first eruptions of Kaharoa Ash were erupted to the south-east. This finding is also supported by the low V contents of the first erupted lava (Crater Dome - Table 16) during the Kaharoa eruption (Cole 1970 d).

Mangaone Lapilli Formation members (c) and (e) show similar general trends. In thick, presumably near source deposits V contents of basal titanomagnetites (Nos. 267, 271, 274 and 278, 286) show a general upward increase. Mangaone member (c) titanomagnetites sampled at distal localities to the SE of the presumed source (Vucetich and Pullar 1969) also contain lower V (Nos. 288, 291). This data indicates that, as with the Kaharoa eruption, the first eruptions of the Mangaone (c) episode were the most violent and deposited tephra over a widespread area to the east and south-east of source.

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* Nos. in Part 1 refer to analysis nos. in Appendix II.

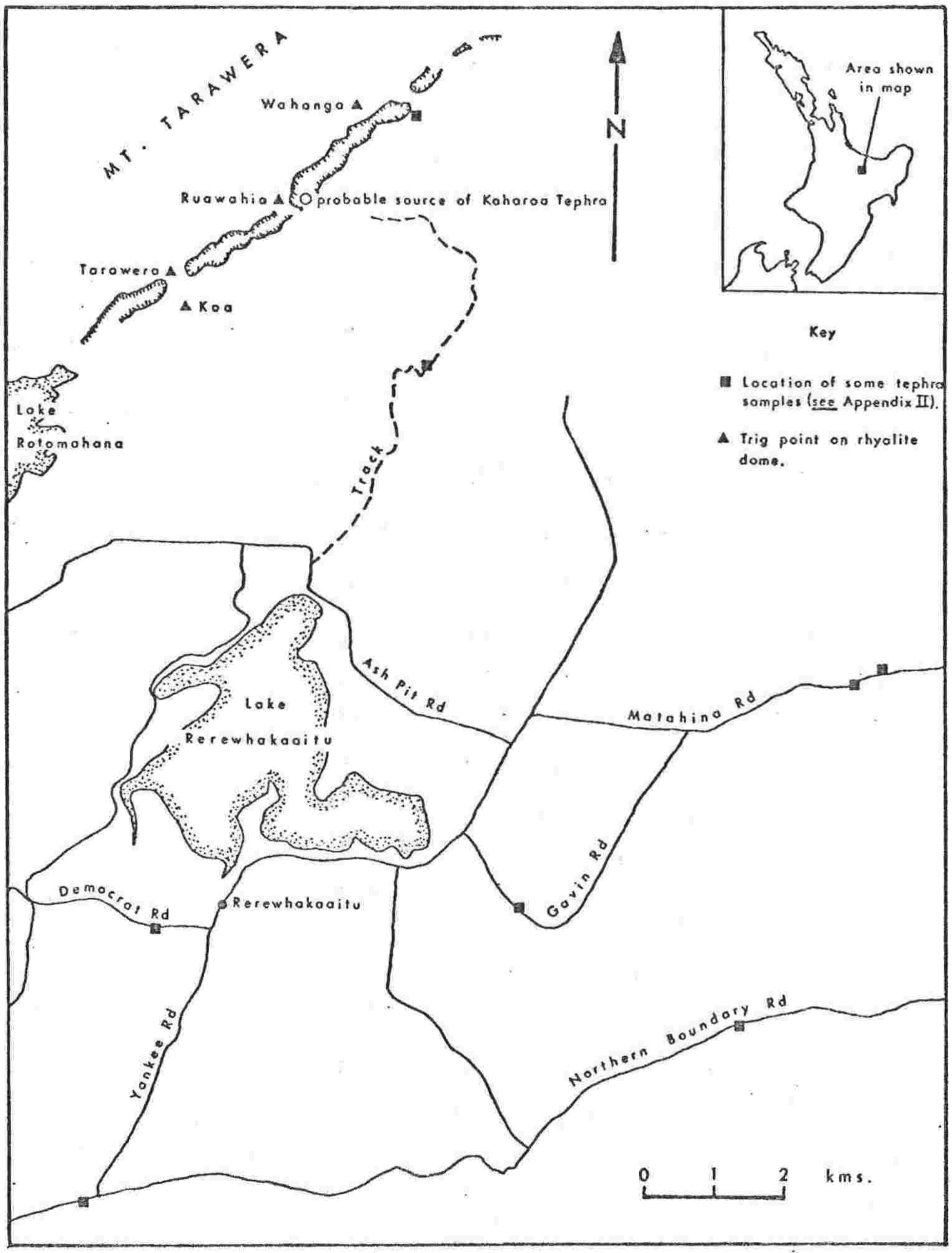

Fig. 14. - Map of the Mount Tarawera - Rerewhakaaitu region, showing locations of some tephra sample sites.

Taupo Sub-Group Member 16

According to Healy (1964), Taupo Sub-group member 16, enclosed by the ^{14}C dated Waimihia Lapilli (c. 3,400 yr B.P.) and Taupo Sub-group members (Tsg.) 17-18 (Opepe Tephra, c. 8,850 yr B.P.), contains five subdivisions labelled a-e with increasing age. Healy considered that Tsg. 16a, contained a paleosol in the upper part, as did Tsg. 16 c, and Tsg. 16 e. This indicates that Tsg. 16, in fact contains the products of three different eruptions (grouped as 16 a, b, 16 c, d and 16 e). Ewart (1963) noted appreciably higher calcic-hornblende contents in Tsg. 16 (especially in the upper part) when compared with other Tsg. members, and on the basis of this mineralogy he concluded that Tsg. 16 was not erupted from the north-eastern Lake Taupo area (Ewart 1964).

An examination of the Tsg. 16 tephras at Iwatahi Gully (Fig 1, Appendix III) 22 km SE of Taupo (N103/735200) showed the following sequence:

Waimihia Formation
Tsg 16
a { 5 cm dark grey brown ash, paleosol, with charcoal fragments
b { 10 cm pale grey ash and fine lapilli, sharp lower contact,

c { 7 cm dark greyish brown ash, paleosol,
d { 15 cm pale olive coarse ash,

e { 15 cm brown ash, paleosol, with charcoal fragments,
{ 2 cm pale yellow fine ash, "cream-cakes".
Opepe Tephra

Samples for mineralogical and chemical analysis were collected from Tsg. 16 b, d and e at Iwatahi.

The ferromagnesian assemblage of 16 b and e contains abundant calcic-hornblende in amounts $\geq$ hypersthene, and that of 16 d contains nearly all hypersthene with rare augite and calcic-hornblende. The abundance of calcic-hornblende in 16 b and e suggest correlation with the Whakatane and Rotoma Ashes respectively, and that of 16 d with the Lake Taupo Volcanic Centre source Hinemaiaia Ash (see Tables 2 and 3). Titanomagnetite analyses of the three tephras 16 b (No. 120), 16 d (No. 130) and 16 e (No. 154) confirm these correlations. A further titanomagnetite analysis from an ash, 7 cm below the base of the Waimihia Formation at Collins Farm (N103/622142) (No. 121) is also similar to Whakatane Ash and contains the slightly higher than average Cr contents also found for this tephra at Iwatahi Gully.

At Iwatahi Gully, the identification of Rotoma Ash rather than Mamaku Ash is supported by the high calcic-hornblende contents (60% of the ferromagnesian assemblage) and also by its known relatively widespread distribution (*see* isopachs Vucetich and Pullar 1964 and Appendix III p. 246).

Radiocarbon ages (Table 2) for the eruption of the three tephras forming Healy's Tsg. 16, also confirm the established stratigraphy.

The Age of Puketarata Ash

Puketarata Dome in Maroa Volcanic Centre (Fig 1) is the source of a grey rhyolitic tephra named Puketarata Ash (Lloyd 1972). The tephra is believed to have been deposited subaerially by eruptions which preceded and accompanied the growth of the dome, and an isopach map showing its distribution is given by Lloyd (1972). Puketarata Ash was assigned an approximate age of c. 10,000 yr B.P. by Lloyd (1972), while Vucetich and Pullar (1969, p. 795) showed it to be older than Karapiti Lapilli but younger than Rotorua Ash.

At a section 6 km SW from source at Palmer Rd (Fig 1, Appendix III N94/542499), 50 cm of Puketarata Ash is enclosed by two rhyolitic tephras each approximately 20 cm thick. Puketarata Ash is identified by its biotite + calcic-hornblende + hypersthene ferromagnesian assemblage (each mineral present in approximately equal amounts) and its titanomagnetite chemistry (Nos. 220,221), both of which are similar to Puketarata Ash at the type locality (Nos. 222, 223).

The ferromagnesian assemblage of the overlying rhyolitic tephra contains dominantly hypersthene with lesser amounts of calcic-hornblende, and traces of augite and biotite, while that of the underlying tephra is dominated by biotite with minor amounts of hypersthene and traces of calcic-hornblende. Titanomagnetite analyses of the tephras (above Puketarata Ash, Nos. 216, 217, 218 - three different grade sizes and below - No. 235) are given in Appendix II. The data indicate that Puketarata Ash at Palmer Rd is overlain by Rotorua Ash (c. 12,500 yr B.P. see Appendix III, p. 251) and underlain by Rerewhakaaitu Ash (c. 14,700 yr B.P.).

At two sections in the Tongariro Region a rhyolitic ash below Rotorua Ash and above the andesitic Rotoaira Lapilli (^{14}C dated at 13,800 ± 300, NZ 1559, Appendix III, Table 2) is considered to be Puketarata Ash (Appendix III, p. 253). The ^{14}C date of Rotoaira Lapilli narrows, the age range of the eruption of Puketarata Ash to $>$12,500 yr B.P. and $<$13,800 yr B.P.

From its relative stratigraphic position to the two enclosing dated ashes in the Tongariro Region, Puketarata Ash is assigned an age of c. 13,500 yr B.P., and this age dates the last known rhyolitic activity from Maroa Volcanic Centre.

Waitahanui Breccia

Grange (1937) proposed the name Waitahanui Series to include a succession of "pumice breccias and tuffs" east of Lake Taupo, at Waiotapu and north of L. Rotoiti. Beck and Robertson (1955) applied the name Waitahanui Breccia to the deposits east of L. Taupo; Thompson (1959) suggested that the name Waitahanui Breccia should be restricted to this usage and that other names should be proposed for the deposits at Waiotapu and north of L. Rotoiti. The deposits "at Waiotapu" were subsequently renamed Earthquake Flat Formation by Grindley (1959). Later Healy et al (1964) proposed the name Rotoiti Breccia to include deposits in the vicinity and north of L. Rotoiti, thus leaving the name Waitahanui Breccia restricted in the sense proposed by Thompson (1959).

Most Waitahanui Breccia in areas to the north, east and south-east of Lake Taupo is thought to correlate with Oruanui Breccia c. 20,000 yr B.P. (Vucetich and Pullar 1969 and Vucetich pers. comm.). General confirmation of this correlation comes from: (a) the mapping of Waitahanui Breccia which is shown to be younger than Tauhara Dacite (K-A dated at 31,000 ± 0.003 yr B.P. - Stipp 1968) and older than the Tsg. tephras near Taupo (oldest c. 9,800 yr B.P.), (Grange 1937, Thompson 1959, Grindley 1960, 1961, Baumgart 1954 and Healy 1964, 1965). (b) titanomagnetite analyses from a tephra flow near Turangi (p. 235) (Nos. 264, 265): a chalazoidite-bearing tephra underlying Taupo Sub-group tephras near Taupo (No. 246) and "Waitahanui Breccia" near Wairakei (Fig 1) (No. 266) show similar chemical composition to titanomagnetites from Oruanui Formation (Appendix II). Of further interest is the correlation of Oruanui Formation with a sample of Wairakei Breccia (P30399, No. 266 a). The similar titanomagnetite composition of these deposits supports the provisional correlation of Oruanui Formation with Wairakei Breccia made by Vucetich and Pullar (1969). All tephras sampled for titanomagnetite, also contain ferromagnesian assemblages similar to Oruanui Formation.

Waitahanui Breccia in the vicinity of Waitahanui Valley, east of L. Taupo, underlies Waimihia Formation (Tsg. 14, Healy 1964, p. 36) and titanomagnetite analyses (Nos. 96-98) from these tephra-flow deposits indicate that they are different from those correlated with Oruanui Formation. The data indicate that they were probably erupted during the same eruptive episode as that which deposited the Waimihia Formation. This correlation is supported by the finding, in the tephra-flow deposits of a hypersthene ferromagnesian assemblage and distinctive grey and grey-and-white banded pumice, both characteristic of Waimihia Lapilli (Ewart 1963).

Data therefore show that most of the Waitahanui Breccia as defined by Thompson (1959) and mapped by Grindley (1960, 1961) is part of the widespread Oruanui and Waimihia Formations. If future mapping, particularly between Waitahanui Valley and Turangi sustains the previous correlations, then the name Waitahanui Breccia (a 'bag-name') will either lapse or have to be redefined.

Oruanui Formation, Yellow Grey Tephra and Aokautere Ash

The name Oruanui Formation was first used by Vucetich and Pullar (1969); they subdivided the formation into two members, Oruanui Breccia and Oruanui Ash. At the type locality on the Wairakei-Putaruru Highway (N94/523521) the following abbreviated sequence was described (Vucetich and Pullar 1969):

3.38 m	Holocene tephra.	
1.82 m	Mokai Sand (reworked Oruanui Formation deposits).	
	Oruanui Formation	
2.13 m	pale brownish grey massive ash, and pumice lapilli tuff, minor rhyolite and andesite lapilli.	Oruanui Brecci
1.52 m	pale olive fine ash (slippery silt) weakly shower-bedded and studded with chalazoidites upto 1.3 cm across.	Oruanui Ash
	sharp boundary	
0.76 m	grey shower-bedded ash, massive,	
0.43 m	pale yellow shower-bedded ash	
0.33 m	pale yellow shower-bedded lapilli	
	sharp boundary	
1.68 m	?Mangaone Lapilli Formation	

In mapping a section at Tumunui Rd in the Earthquake Flat area (N76/733905), Naira (1971) recognised the following abbreviated sequence:

2.77 m	Holocene tephra	
	eroded to and some loess	
0.90 m	Okareka Ash	
0.65 m	Te Rere Ash with some loess in upper part	
0.32 m	pink grey fine ash with chalazoidites	
0.025m	white fine ash	Oruanui Formation
0.01 m	white fine to medium ash	
0.025m	white fine ash	
0.45 m	loose roughly bedded yellow reworked ash containing biotite, quartz and feldspar - thickness variable	Loess

0.25 m	olive grey fine ash	"yellow-grey tephra"
0.15 m	yellow and white medium ash	
0.05 m	yellow and white fine ash	
	sharp contact	
1.73 m	Mangaone Lapilli Formation	

At other sections between the Tumunui Rd area and the Oruanui type section to the south, the "yellow grey tephra" is separated by loess or by a weak paleosol from the overlying fine shower-bedded base of the chalazoidite bearing Oruanui Ash, and is underlain directly by the upper Mangaone Lapilli members. This evidence strongly suggests that the "yellow-grey tephra" is correlated with the massive grey ash and basal shower-bedded yellow ash and lapilli of the Oruanui Formation at the type locality.

Although not specifically described at the type section, a 9 cm thick finely shower-bedded ash is intercalated between the chalazoidite-bearing ash and the underlying massive grey ash. The 9 cm bed wedges-out laterally and appears to have been deposited on an eroded surface, thus indicating a time interval between the "yellow-grey tephra" and overlying shower-bedded tephra. The finely shower-bedded tephra is a distinctive deposit and forms the basal bed of the Oruanui Formation over a wide area (e.g. Tumunui Rd section), suggesting that this bed has been largely eroded at the type locality.

The Oruanui Ash should thus be redefined to include only the chalazoidite ash and its finely shower-bedded base at the present type locality, and that a new type locality, less eroded, be designated. The underlying "yellow-grey tephra" previously mapped as part of Oruanui Ash on the basis of intervening time, different lithology and different distribution, was considered by Nairn (1971) to be a separate formation.

The lowest shower-bedded ash and lapilli of Oruanui Ash at the type section was provisionally correlated by Vucetich and Pullar (1969) with Aokautere Ash in the Manawatu District (Cowie, 1964). This provisional correlation implies that Nairn's "yellow-grey tephra" is also equivalent to Aokautere Ash. The stratigraphic sequence of Aokautere Ash (and Oruanui Ash) consists of shower-bedded tephra conformably overlain by chalazoidite-bearing ash. Stratigraphy therefore shows that most if not all of the Aokautere Ash is probably equivalent to Oruanui Ash (i.e. above the 0.76 m grey ash), but that at the type locality most of the shower-bedded base has been eroded.

Oruanui Formation has also been correlated with Wairakei Breccia (see p. 106); the latter being defined, from a drill-hole in the Wairakei Geothermal Field by the first incoming of chalazoidites (Grindley 1965a). The upper chalazoidite beds of the Wairakei Breccia are probably associated with later tephra-fall beds which were deposited towards the end of the Oruanui eruption, but as the Oruanui Breccia is invariably eroded these beds are not now known to be preserved above surface. It is probable that these later erupted air-fall beds also contributed to the upper part of the Aokautere Ash nearer source, much in the same way as air-fall beds underlying, intercalated with and overlying Rotoiti Breccia all contributed to the Rotoehu Ash beyond the extent of the tephra-flow deposits (Nairn 1972).

The stratigraphic relationship of Oruanui Formation, "yellow-grey tephra" and Aokautere Ash is shown in Fig 15.

The ferromagnesian contents of Oruanui Formation, "yellow-grey tephra and Aokautere Ash are similar (Table 2).

Titanomagnetite compositions for Oruanui Breccia (Nos. 264-266), Oruanui Ash (Nos. 244-251, 253, 254), Aokautere Ash (Nos. 256-263) and "yellow-grey tephra" (Nos. 241-243, 252) analysed by optical emission spectroscopy are given in Appendix II and those for the same formations analysed by electron microprobe in Table 15. With the exception of the upper massive grey ash which is more basic, and the generally higher Cr values in chalazoidite beds from Oruanui Ash and Aokautere Ash, all titanomagnetite compositions are similar. The more basic composition of titanomagnetite from the upper part of the grey ash (No. 243) may be due to contamination of this bed during the time interval between the "yellow-grey tephra" and Oruanui Formation eruptions.

The stratigraphic, mineralogical and chemical evidence indicate that the Aokautere Ash is a distal correlative of

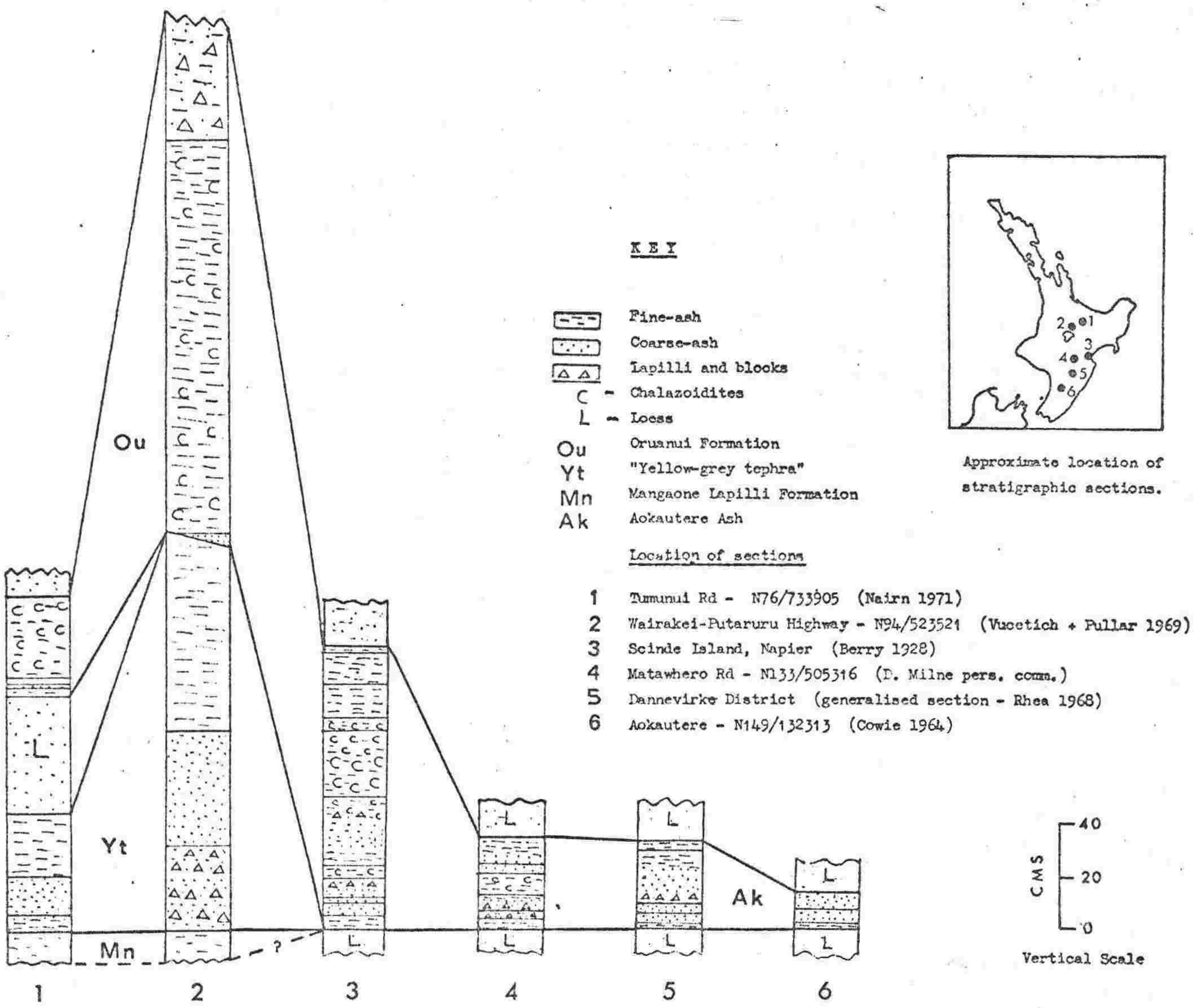

Fig. 15. - Correlation line showing stratigraphic relationship of "Yellow-grey tephra" and Aokautere Ash with Oruanui Formation at the type locality (section 2). Full thickness of Oruanui Breccia at section 2 is not shown.

Table 15. - Electron micro-probe analyses of titanomagnetites from Oruanui Ash, Aokautere Ash and "Yellow-Grey Tephra". Analyses by Mr. P.R. Kyle (using the electron microprobe analyser of the Geology Department, Otago University - see Table 14 for operating details).

SAMPLE NO.	1	2	3	4	5	6	7	8
%								
SiO_2	0.02 ± 0.01	0.05 ± 0.03	0.02 ± 0.01	0.05 ± 0.01	0.04 ± 0.02	0.08	0.05	0.04
TiO_2	10.02 ± 0.21	9.94 ± 1.01	10.62 ± 0.11	10.10 ± 0.79	10.21 ± 0.73	10.58	10.58	10.48
Al_2O_3	1.59 ± 0.04	1.58 ± 0.09	1.53 ± 0.03	1.59 ± 0.03	1.57 ± 0.05	1.51	1.54	1.55
V_2O_3	0.29 ± 0.01	0.60 ± 0.08	0.21 ± 0.03	0.50 ± 0.19	0.44 ± 0.20	0.55	0.55	0.56
FeO	82.74 ± 0.29	82.02 ± 0.87	82.22 ± 0.11	82.03 ± 0.76	82.08 ± 0.61	81.30	81.71	81.78
MnO	0.51 ± 0.02	0.55 ± 0.10	0.59 ± 0.01	0.57 ± 0.07	0.57 ± 0.06	0.62	0.59	0.59
MgO	0.73 ± 0.02	0.66 ± 0.09	0.63 ± 0.01	0.67 ± 0.08	0.66 ± 0.07	0.59	0.61	0.63
Sum	95.90	95.40	95.82	95.51	95.57	95.23	95.63	95.63
Recalculated analysis (Ulvospinel basis)								
Fe_2O_3	48.32	47.68	47.14	47.53	47.54	46.25	46.60	46.82
FeO	39.26	39.12	39.80	39.26	39.28	39.68	39.78	39.65
Total	100.74	100.24	100.54	100.27	100.31	99.86	100.30	100.32

Key to sample nos.

1 "Yellow-grey tephra" *11875 - average (± 1 s.d.) of 4 analyses.
2 Oruanui Ash - chalazcidites, 11877 - average (± 1 s.d.) of 3 analyses.
3 Oruanui Ash - chalazoidites, (analysis no. 247 - Appendix II) - average (± 1 s.d.) of 3 analyses.
4 Aokautere Ash (analysis no. 259 - Appendix II) - average (± 1 s.d.) of 4 analyses.
5 Average Oruanui Ash + Aokautere Ash based on 10 analyses (nos. 2,3 and 4 above).
6 11875 titanomagnetite grain enclosed by glass.
7 11875 " " " " " hypersthene.
8 11875 discrete titanomagnetite grain.

* Numbers refer to samples housed in the petrological collection, Geology Department, Victoria University.

Oruanui Ash, (i.e. tephra above the grey bed at the present Oruanui Formation type locality). It is also probable that tephras associated with Oruanui Breccia eruptions also contribute to Akautere Ash, but these appear to have been eroded.

Correlation of Tephra and Lava of the Same Eruptive Episode

It was suggested by Kohn (1970) that a probable application of using titanomagnetite chemistry was in correlating all the products of a single eruptive episode.

Results for titanomagnetite analyses of tephra-fall and tephra-flow deposited during the same eruptive episode are given in Appendix II. Tephra-flows of Kaharoa (No. 34), Waimihia (Nos. 96-98), Oruanui (Nos. 264-266), Earthquake Flat Breccia (No. 321) and Rotoiti Breccia (Nos. 338-343) eruptions all contain comparable titanomagnetite compositions to those of their tephra-fall correlatives.

Table 16 shows titanomagnetite analyses from lavas (domes) extruded during the same eruptive episode as some tephras. With the exception of Puketarata Dome (Lloyd 1972), all lavas studied were erupted from Mt Tarawera (Fig 1), where lavas and their tephra-correlatives are known (Cole 1970d).

The data in Table 16 confirms previous correlations (see Table 6 for averaged tephra-fall analyses). The relatively higher V values confirm that Plateau Dome and Waiohau Tephra were erupted during the Waiohau eruption (Cole 1970d). Of particular interest is the lower V content of Crater Dome which was the first lava extruded during the Kaharoa eruption. This finding confirms the interpretation of previous data from earliest Kaharoa Tephra which was erupted immediately after the extrusion of Crater Dome.

The evidence presented shows that in the eruptions studied all the products (tephra and lava) of a volcanic episode have comparable titanomagnetite composition despite their differing mechanisms of deposition.

TEPHRA ASSOCIATED WITH DOME EXTRUSION	DOME	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
KAHAROA	Wahanga	4.80	0.50	0.87	0.48	1178	63	26	19	752	25
	Wahanga - Top of pinnacle	5.03	0.42	0.76	0.53	1130	38	21	15	1135	32
	Wahanga - centre of onion-skin, much secondary titanomagnetite	4.99	0.52	0.74	0.23	1301	44	28	16	241	15
	Ruawahia - edge	5.13	0.39	0.81	0.22	1201	35	24	47	1502	25
	Crater	4.19	0.70	1.06	0.78	924	45	43	25	-	-
WAIOHAU	Plateau	5.16	0.72	0.67	0.19	1638	75	52	27	164	23
REREWHAKAAITU	Koa - phenocryst-poor	4.63	0.64	0.54	0.60	1342	57	37	22	859	19
	" - " "	5.05	0.69	0.65	0.33	1510	50	42	38	680	44
	" - phenocryst-rich	5.15	0.47	0.70	0.52	1810	145	48	42	505	35
PUKETARATA	Puketarata - P29115	5.43	0.37	0.66	0.37	1893	228	60	91	157	76

- not determined.

Table 16. - Analyses of titanomagnetites from rhyolite domes extruded during the same eruptive episode as some tephras. Information on analyses as for Table 6.

Sources of Tephra Contamination

Titanomagnetite analyses of samples taken from the upper parts of rhyolitic tephras or from within paleosols show that many are contaminated by andesite. Of particular interest is titanomagnetite taken from Tsg. 19 (the top of Poronui Tephra - Vucetich and Pullar 1973) at four localities. The analyses of the titanomagnetites (Nos. 177-180), as well as titanomagnetite taken from the paleosol of underlying Karapiti Lapilli (No. 192) are andesitic in composition (see Table 17 for andesite titanomagnetite analyses). The presence of andesitic tephra (identified as Poutu Lapilli - Appendix III) explains the anomalous (more basic) mineralogy and chemical composition of minerals found in Tsg. 19 by Ewart (1963, 1967b, 1971a). The andesitic composition of titanomagnetite from Tsg. 26 (Nos. 193-195) also explains the more basic mineralogy (more augite) of this deposit found by Ewart (1963).

Andesitic contamination of the paleosol of Waiohau Ash (No. 207) in the Opotiki area (Fig 1) and in the finer grade size of Rerewhakaaitu Ash (No. 230) in the Mt Tarawera area, is indicated by the more basic composition of their titanomagnetites. Titanomagnetite samples from the paleosols of Mangaone Lapilli Formation members (c) (No. 283) and (e) (No. 269) show more basic values than those sampled from lower pumice blocks and lapilli. The Cr values of the titanomagnetites taken from the paleosols are not high enough to suggest andesitic contamination. However, the values are similar to the older more-basic Mangaone Lapilli members which could have been reworked and deposited in the paleosols as tephric loess.

Titanomagnetite from the paleosol of Rotoehu Ash (No. 290) at Waipaoa near Gisborne (Fig 1) has a composition typical of the immediately overlying Mangaone Lapilli member (c). This indicates Mangaone member (c) has contaminated the paleosol of Rotoehu Ash. The lack of titanomagnetite characteristic of the older Mangaone members in the Rotoehu paleosol implies that these tephras can be represented in the Gisborne area only in small amounts.

The presence of contamination in rhyolitic-tephra paleosols, by loess and from overlying tephra, and especially by andesitic tephra (from Tongariro Region not from Mt Egmont area, c.f. Table 17 and Table 2 - Appendix IV) indicates that care must be taken in attempting any weathering or paleo-pedological studies of these buried soils.

6. THE RELATIONSHIP BETWEEN RHYOLITIC AND ANDESITIC VOLCANISM OVER THE PAST c. 10,000 YRS

Rhyolitic tephras from Okataina, Maroa and Lake Taupo Volcanic Centres have been identified within the Tongariro Region (Appendix III). The distribution of these tephras through time and their relationship to major andesitic tephras is shown in Table 1, Appendix III.

Tephras erupted from Okataina and Maroa Volcanic Centres appear to be unrelated to andesitic volcanism. But eruption of the older Taupo Subgroup tephras appears to be related in time to andesitic eruptions.

Stratigraphic Evidence The most widespread and persistent andesitic tephra beds, Poutu Lapilli and Te Rato Lapilli, each comprise several lapilli units erupted over a very short period of time (approximately 9,740-9,780 yr B.P.) mainly from the Tama Lakes region of Tongariro (Fig 1, Appendix III). This activity almost coincides with deposition of Karapiti Lapilli, Papanetu Tephra and Poronui Tephra, and extrusion of Kuhurua Dome.

The frequency and duration of andesitic tephra eruptions decreased sharply about 8,250 yr B.P. (W.W. Topping pers. comm.), some 600 yrs after eruption of Opepe Tephra. This decline in andesitic volcanism allowed a thick paleosol (Papakai Tephra) to develop over a period of approximately 3,400 yrs (Topping 1973). This is the only obvious paleosol in andesitic tephra sections north of Tongariro above Oruanui Formation.

Whakatane and Rotoma Ashes erupted from Okataina Volcanic Centre undoubtedly reached Tongariro but because they were thin and deposited post-8,000 yr B.P. they were incorporated into the developing soil (Papakai Tephra) and are therefore no longer preserved as discrete layers. Hinemaiaia Ash was erupted c. 6,000 yr B.P. from a source about 60 km further south than the two Okataina-source tephras and its greater thickness allowed it to be preserved as a discrete layer.

About 4,800 yr B.P. andesitic volcanism began again with extensive activity from Ngauruhoe and Red Crater (Topping 1973) and eruption of tephra from these vents together with that from Ruapehu (see Fig 1, Appendix III for localities) has continued to the present day. Deposition of this andesitic tephra in the Tongariro area has been interrupted by the larger rhyolitic Waimihia Lapilli and Taupo Pumice, and smaller Whakaipo Tephra and Mapara Tephra eruptives from the Lake Taupo Volcanic Centre.

Periodicity of the Taupo Subgroup tephras is shown in Table 2. The eruption of Hinemaiaia Ash from Lake Taupo Volcanic Centre c. 6,000 yr B.P. does not support the suggestion by Ewart (1964) that a 5,000 yr quiescent period preceded eruption of the Waimihia Lapilli.

Chemical Evidence Titanomagnetite and ilmenite are generally the first minerals that co-precipitate from the magmas under study (Ewart 1963). Element concentrations within the titanomagnetites probably therefore reflects the availability of elements which can be favourably incorporated into the lattice making them sensitive recorders of changes in magma ~~concentration~~ composition.

Titanomagnetite analysed from all formations of the Taupo Subgroup (Appendix II) show two groupings which are considered to reflect differing compositions of magmas, the older group comprising Karapiti Lapilli, Poronui Tephra and Opepe Tephra, and the younger group comprising Hinemaiaia Ash and younger tephras. These two "magmas" are also grouped on the basis of vesicularity of pumice, the chemistry of their glasses, and pressure conditions under which they were erupted (older magma at 1,000 Kg/cm^2, younger magma at 2,000-3,000 Kg/cm^2) (Ewart 1963).

Titanomagnetites from andesitic tephras and associated lavas erupted over approximately the last 20,000 yrs from Tongariro and Ruapehu have been analysed (Table 17) and these also fall into two distinctive groups. Plots showing the two groupings for rhyolites and andesites are shown in Fig 16 (vanadium v's chromium) and Fig 17 (nickel v's cobalt). The older andesitic grouping is represented by tephra and lavas older than Okupata Tephra c. 10,000 yr B.P. (see Table 1,

ANDESITIC TEPHRA AND LAVA

Analysis No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
1	Ngauruhoe Tephra	Desert Road	N112/250787	5.06	1.96	0.45	0.47	5184	914	175	289	98	101
2	Mangatawai Tephra	Makahikatoa Bridge Desert Road basal 40 cm	N112/250787	3.33	1.79	0.21	1.08	3572	726	136	239	121	200
3	Papakai Tephra	Desert Road ash within paleosol	N112/250787	6.73	1.64	0.50	0.17	4552	812	187	277	85	108
4	Poutu Lapilli	National Park-Taupo Road	N112/239901	5.77	1.15	0.43	0.66	4954	1706	163	322	103	170
5	Poutu Lapilli	S.E. of Blue Lake	N112/166833	2.64	1.54	0.38	1.45	3136	958	198	289	56	269
6	Poutu Lapilli	Desert Road	N112/298951	2.97	0.79	0.28	2.64	3206	764	128	225	74	93
7	Poutu Lapilli	Iwatahi Gully in paleosol on Poronui Tephra	N103/735200	5.39	1.47	0.38	0.46	4913	562	142	217	138	96
8	Te Rato Lapilli	Te Ponanga Road	N112/221978	3.64	0.66	0.30	1.17	4337	960	163	284	70	121
9	Te Rato Lapilli	Ketetahi Springs finely vesiculated lithic fragments	N112/139872	5.06	1.35	0.33	0.62	4203	1502	156	248	88	171
10	Te Rato Lapilli	Okahukura Bush (N. Tongariro) pumiceous lapilli	N112/153902	3.31	1.09	0.35	0.44	1628	93	72	53	16	52
11	Te Rato Lapilli	Iwatahi Gully	N103/735200	6.57	1.00	0.43	0.16	4363	475	104	176	204	91
12	Okupata Tephra	National Park-Taupo Road upper ash	N112/037866	6.91	1.63	0.25	0.30	5797	2212	176	366	108	75
13	Okupata Tephra	National Park-Taupo Road	N112/037866	5.72	1.80	0.24	0.63	5019	1843	192	338	76	118
14	Unnamed tephra (below Okupata T)	National Park-Taupo Road basal lapilli	N112/037866	5.39	1.90	0.25	0.27	4981	2284	209	446	76	105
15	Unnamed tephra (below Okupata Tephra)	Near Hydro Access Road	N112/105987	5.87	1.87	0.26	0.34	5367	2242	202	380	74	248

Analysis No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
16	Unnamed tephra (below Okupata T)	National Park-Taupo Road	N112/069918	6.41	1.99	0.31	0.27	6899	2509	221	453	67	95
17	Rotoaira Lapilli	National Park-Taupo Road	N112/239901	7.13	1.46	0.24	0.24	6401	1941	186	393	95	164
18	Rotoaira Lapilli	Rotoaira Road	N112/158980	7.41	1.80	0.35	0.27	~9870	2472	219	499	108	180
19	Te Mari Lava Flow	Lower Te Mari Crater upper flows	N112/161872	7.14	1.50	0.28	0.30	7037	1791	225	371	108	133
20	Te Mari Lava Flow	Lower Te Mari Crater lower flows	N112/161872	7.24	1.18	0.26	0.29	6120	1345	198	314	119	136
21	Unnamed andesitic tephra below Rotoaira Lapilli	Desert Road	N112/291879	7.98	1.74	0.36	0.13	5326	2056	315	531	198	181
22	Unnamed andesitic tephra below Rotoaira Lapilli	Poutu Canal	N112/289880	6.29	1.92	0.30	0.23	~11893	1951	202	387	127	79
23	North Crater - young lava	North Crater	N112/136855	8.42	1.07	0.29	0.15	~8809	2470	173	280	106	110
24	Blue Lake lava	Blue Lake, western rim	N112/148846	6.91	0.99	0.23	0.13	~10077	~6325	221	470	114	122
25	Old North Crater lava	North Crater, eastern rim	N112/143851	7.54	0.90	0.29	0.18	~8236	~21107	221	411	197	108

Table 17. - Titanomagnetite analyses of andesitic tephras and lavas erupted from the Tongariro Volcanic Centre and correlatives at Iwatahi (Fig. 1 - Appendix III). Information on analyses as for Table 6.

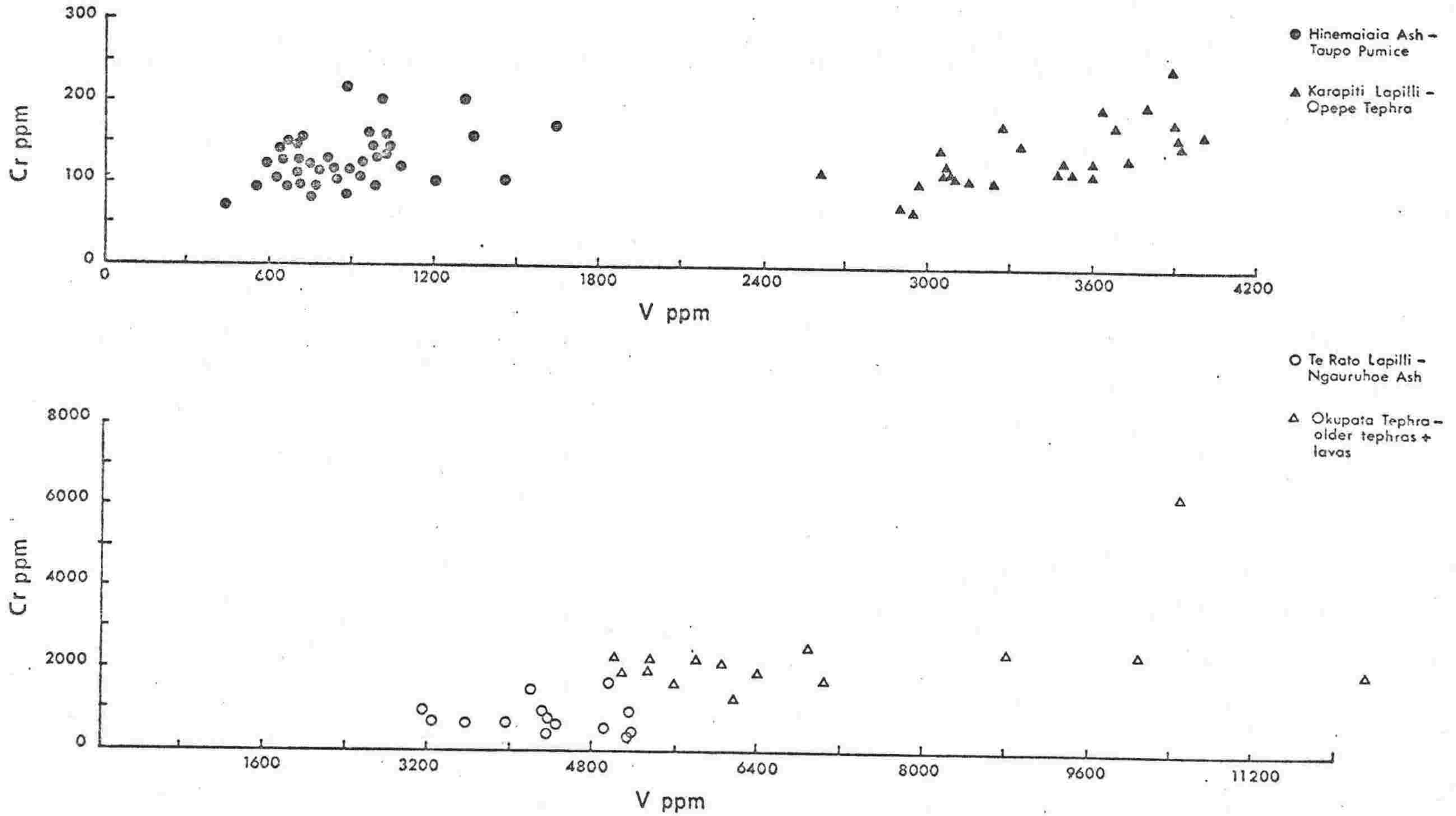

Fig. 16. - Plots of Cr versus V compositions of titanomagnetites from the rhyolitic Taupo Sub-group tephras (upper diagram) and the andesitic Tongariro Sub-group tephras and lavas (lower diagram).

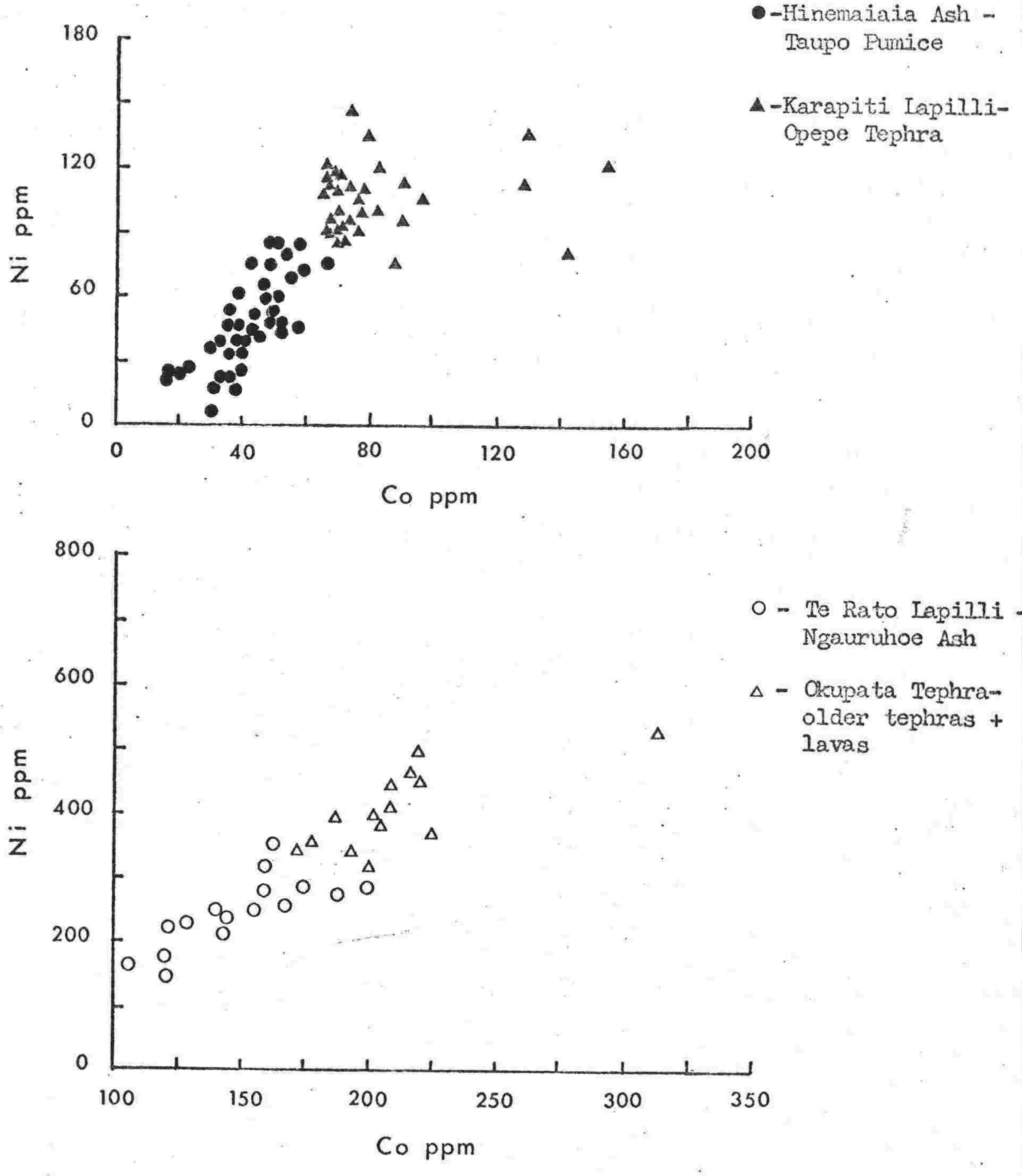

Fig. 17. - Plots of Ni versus Co compositions of titanomagnetites from the rhyolitic Taupo Sub-group tephras (upper diagram) and andesitic Tongariro Sub-group tephras and lavas (lower diagram).

Appendix III).

Changes in composition of titanomagnetites suggest that tephras erupted from Tongariro Volcanic Centre within the past c. 10,000 yr B.P. crystallized from a "less-basic" andesitic magma. The first eruptions of this new magma (oldest analysed - Te Rato Lapilli, see Table 17) were the most voluminous and widespread (Topping 1973) and were very closely associated in time with the eruption of the Karapiti Lapilli and Poronui Tephra (Appendix III). The older rhyolitic eruptions ceased about 8,850 yr B.P. approximately 600 yr before andesitic tephra accumulation dropped sharply. Some 2,000 yrs later, rhyolitic tephra of different composition was produced in the Taupo area with the eruption of Hinemaiaia Ash.

It has been suggested by Ewart (1964) that an initial build-up in vapour pressure was responsible for each eruptive sequence of the Taupo Subgroup, although this was not necessarily the triggering mechanism. It is here suggested that the upward movement of andesite magma of new composition and its initial relatively violent eruption c. 10,000 yr B.P. may have provided the trigger for eruption of the oldest Taupo Subgroup tephras. The periodicity of subsequent rhyolitic eruptions is considered to be controlled by increase of vapour pressure over confining pressure or by the rise of acid magma in response to regional subsidence (Ewart 1964), with the intermittent "small-scale" andesitic volcanism having no significant effect on the timing of eruptions.

7. WEATHERING OF TEPHRA

Introduction

The principal changes occurring during chemical weathering of the acidic tephras being studied are decrease of silica and mobile cations and increase in hydroxyl water (water of hydration above 110°C, denoted as loss on ignition L.O.I. in Table 4). In terms of increase in degree of chemical alteration, Ti, Fe and Al increase, Mg does not show a noticeable trend and Ca, K and Na decrease. Solubility is one of the major factors affecting the accumulation or removal of an element during weathering. Ionic potential (I.P., defined as the ionic charge of an element divided by its ionic radius) controls the solubility through its effect on the complex that the element will form in water. Cations with I.P. < 3.0 (Na, K and Ca) tend to form soluble cations in water, cations with I.P. between 3 - 12 (Fe, Al and Ti) tend to form insoluble hydroxides (Keller 1957). Mg has an I.P. of 3, a value located on the boundary between soluble cations and insoluble hydroxides and this may account for its variation.

Thus as tephra continues to weather it will appear to become more "basic" in composition (e.g. a vertical profile through Rotorua Ash from fresh basal pumice blocks 11864 through an intermediate horizon 11865 to the paleosol 11866, see Table 4). The relative changes in elemental composition are in agreement with weathering trends in tephras from United States (Hendricks and Whittig 1968 and Bockheim et al 1969), New Guinea (Ruxton 1968a), Hawaii (Atkinson and Swindale 1971) and Japan (Aomine and Wada 1962).

Scope and Method of Study

Attempts to quantify weathering in terms of time are complicated by differential weathering of varying size grades (e.g. in Table 4, three different size grades of Rerewhakaaitu Ash, 11868 finest-ash size, 11869 intermediate and 11870 coarsest-lapilli and blocks), the possible presence of contaminants (e.g. andesitic tephra within paleosols, as in older Taupo Subgroup tephras see p. 115) and variable environmental conditions at different sites.

Pumice blocks and lapilli (of similar density) were sampled vertically from a thick sequence of six Mangaone Lapilli Formation members at one locality. The Mangaone Lapilli members, enclosed by the ^{14}C dated Oruanui and Rotoehu Ashes, have been analysed for major elements in order to determine the relative time intervals between eruptions. Sampling of the coarsest tephra at one near source site largely overcomes problems outlined above.

Mangaone Lapilli members were chosen for this study because: (i) most have not yet been dated (the only reliable time control being a ^{14}C date of 30,100 ± 1,300 yrs B.P. on charcoal from a tephra-flow within Mangaone Lapilli member (c)); (ii) near source members largely comprise thick pumice block and lapilli beds; (iii) paleosols contain pumice fragments and these are not always common in paleosols of other tephras; (iv) acidic lapilli and blocks of central North Island tephras show greater amounts of weathering when older than c. 20,000 yrs B.P. (first appearance of hydrated halloysite).

Petrographic evidence, based on amount of etching of phenocrysts, shows that glass is the main constituent of Mangaone Lapilli members which is weathering.

Stratigraphy and Lithology

The locality chosen for this study is at Braemar Rd (N68/201265) Bay of Plenty. The section, recently exposed on the left side of the road going north, has an easterly aspect and is sited slightly to the west of the point where the lower slopes of the uplands and hills of the western Bay of Plenty meet the flat lying Rangitaiki Plains. The site occurs on a gentle slope at c. 25 m above sea-level, is well drained and receives between 1270-1525 mm rainfall per annum.

The following conformable, almost flat lying stratigraphic sequence was measured at Braemar Rd (Fig 18):

Fig. 18. - Tephra sequence at Braemar Road (N68/202265) showing Mangaone Lapilli Formation members b_1 - e. Member (a) overlying Rotoehu Ash is exposed just above road level to the right of the photograph.

Holocene Tephra Beds
191 cm

Oruanui Ash - Or
31 cm pale grey ash
3 cm fine lapilli

Mangaone Lapilli - Mn

member (e) - Mn (e)
15 cm paleosol, olive brown ash with scattered weathered pumice blocks + lapilli.
25 cm weathered pumice (can be crushed with fingers) with olive brown ash and lapilli.
102 cm olive white lapilli and blocks, and lithic fragments which may comprise upto 40%, faint semblance of shower bedding, pumice blocks upto 6 cm across.
142 cm

member (d) - Mn (d)
14 cm weak paleosol, olive brown, mainly grey ash with occasional lapilli and blocks.
17 cm yellow lapilli with three shower bedded units, unit as a whole fines upwards.
31 cm

member (c) - Mn (c)
25 cm paleosol, olive grey ash, reddy brown in parts, contains weathered pumice blocks.
94 cm white lapilli and blocks, loosely wedged, some pinkish pumice larger blocks towards base, lithics comprise upto 30%, unit fines upwards.
124 cm white lapilli and blocks, with coarse ash and fine lapilli bands, some beds of lithic fragments, blocks upto 3 cm across.
8 cm white pumice blocks upto 8 cm across.
14 cm grey ash with occasional pumice blocks and lapilli.
265 cm

member (b_2) - Mn (b_2)

23 cm olive and strong brown paleosol mainly ash, with 'rotten' pumice lapilli increasing downwards.
86 cm yellow lapilli and blocks, 10% pink, tightly packed, increasingly weathered towards top of unit, generally fining upwards.
28 cm olive yellow lapilli and coarse ash, loose.
137 cm

member (b_1) - Mn (b_1)

upto 23 cm black paleosol (10YR 3/2), coarse ash with some lithics and blocks, not well developed paleosol.
157 cm pink lapilli and blocks of pink pumice throughout comprises upto 20%, abundant lithics upto 40%, rest of bed mainly white blocks and lapilli, shower-bedded, unit fines upwards.
180 cm

member (a) - Mn (a)

32 cm brown greasy paleosol, fine ash.
10 cm whitish "cream cakes" in darker ash and fine lapilli, bed fines upwards.
13 cm pink ash and fine lapilli.
10 cm yellow ash + fine lapilli, with whitish cream cakes at base, some lithics.
65 cm

Rotoehu Ash - Re

31 cm brown greasy paleosol passing down gradually into whitish ash (112 cm +) to road level.

According to Vucetich and Pullar (1969) only five Mangaone Lapilli members occur, labelled (a) to (e) in order of decreasing age. At Braemar Rd, two tephras occur between members (a) and (c) and these are here labelled (b_1) - older and (b_2) - younger, both are dacitic in composition (Table 4).

Quantitative measures of the degree of chemical weathering of rocks have been reviewed and discussed by Ruxton (1968b), who suggested that the mole ratio of silica to alumina may be the most useful. The ratio, however is subject to a number of restrictions as to its use (Ruxton 1968b). To overcome these restrictions Parker (1970) has proposed a weathering index (here termed Parker's Index, P.I.) for silicate rocks, which is not subject to restrictions and is, therefore, more widely applicable. It takes into account the individual mobilities of the most mobile major elements, based on bond strength considerations. Although silica is mobile during weathering its movement within a profile is often irregular and the total proportion lost maybe small. Silica is therefore not used in deriving Parker's Index.

The index is defined as (after Parker 1970):

$$\frac{(Na)_a}{(Na\text{-}O)_b} + \frac{(Mg)_a}{(Mg\text{-}O)_b} + \frac{(K)_a}{(K\text{-}O)_b} + \frac{(Ca)_a}{(Ca\text{-}O)_b} \quad X \ 100$$

where X_a indicates the atomic proportion of element X, defined as atomic percentage divided by atomic weight, and $(X\text{-}O)_b$ is the bond strength of element X with oxygen. Using values for bond strength, the expression becomes

$$\frac{(Na)_a}{0.35} + \frac{(Mg)_a}{0.9} + \frac{(K)_a}{0.25} + \frac{(Ca)_a}{0.7} \quad X \ 100$$

P.I.s have been derived for all analyses from pumices of the Mangaone Lapilli Formation members (see Table 4).

Two methods have been used for dating eruptions of Mangaone Lapilli members.

(1) Within each member the lowest P.I. value (most weathered pumice) has been subtracted from the highest P.I. value (freshest pumice). The sum of all the residual P.I.s is then divided into 24,000 (i.e. the approximate number of ^{14}C years between Oruanui and Rotoehu 'eruptions') and a value of decrease of P.I. units /1000 yrs is derived. This value is then divided into the residual P.I. for any one member, and approximate number of years between eruptions derived. Dates for eruption of Mangaone Lapilli members calculated by this method are given below:

	Approx. duration of weathering between eruptions (x10^3 ^{14}C yrs)	Approx. date of eruption (x10^3 ^{14}C yrs)
Or		
	5.4	
Mn (e)		25.4
	0.1	
Mn (d)		25.5
	4.4	
Mn (c)		29.9
	4.5	
Mn (b_2)		34.4
	1.3	
Mn (b_1)		35.7
	4.2	
Mn (a)		39.9
	4.2	
Re		

(2) Within each member the lowest P.I. value was subtracted from the average P.I. value 70.6 for rhyolite and dacite, (average values for rhyolite and dacite fresh rocks - from Ewart (1966) average values, and glass analyses in Table 5) and a value for number of years between eruptions then calculated as in (1) above. Dates for eruption of Mangaone Lapilli members calculated by this method are given below:

	Approx. duration of weathering between eruptions (x10^3 ^{14}C yrs)	Approx. date of eruption (x10^3 ^{14}C yrs)
Or		
	4.9	
Mn (e)		24.9
	1.5	
Mn (d)		26.4
	3.3	
Mn (c)		29.7
	3.8	
Mn (b_2)		33.5
	2.1	
Mn (b_1)		35.6
	4.2	
Mn (a)		39.8
	4.2	
Re		

Discussion

In deriving approximate dates for Mangaone Lapilli eruptions the following assumptions have been made.

(i) That the time for paleosol development on Rotoehu Ash and Mangaone Lapilli member (a) was approximately equal. This assumption was made because only fine lapilli and ash size grade material occur at Braemar Rd. P.I. values on these size grades indicate the same degree of paleosol development by method (1) and 1,000 yrs longer for the finer size grade Rotoehu Ash by method (2).

(ii) That the P.I. values for original tephra did not vary markedly within a member (pink pumice was not sampled in this study as it was probably partially hydrothermally altered), this is borne out by the small range for numerous rhyolites and dacites for which average P.I. = 70.6 ± 2 (P.I. values for some dacite glasses and rocks ranged between 71-73, indicating their slightly higher susceptibility to weathering). Using slightly higher values for dacite by method (2) makes dates on the upper five Mangaone Lapilli members slightly younger, with longer periods of weathering between eruptions of the older dacitic members.

(iii) That the effect of climatic changes in the past has had no marked effect on weathering indices as measured today. For instance it is known that a stadial commenced in New Zealand c. 35,000 yrs B.P. (Fleming 1972). This may have caused decreased weathering rates, making measured time intervals between eruptions of the older Mangaone Lapilli members longer; conversely an interstadial between c. 24,000-30,000 yrs B.P. (Brodie 1957) may have increased the weathering rate, making measured intervals between the younger members shorter and ages of eruptions older. Alternatively, it is possible that member (e) is younger than indicated and that its apparent long period of weathering is due to the relatively thin, fine tephra layers, deposited at intervals over the last 20,000 yrs, which give it little protection from continuing weathering.

(iv) That the most weathered tephra is the one with the lowest P.I.; this is not always within the paleosol, although it is usually in the upper half of a tephra unit.

(v) That there is no concentration of cations within the sequence and that any cation input with rainfall does not affect analyses to any extent. These assumptions are borne out by the analyses of ash, lapilli and blocks (Table 4) which show predictable elemental contents according to size and position in the sequence.

Despite the assumptions that have been made, the use of P.I.s using methods previously described provides a time scale for Mangaone Lapilli eruptions including ages for member (c) which are within the range of the ^{14}C date for this eruption. Furthermore, members (d) and (b_1) show the weakest paleosol development respectively, and this is reflected in the relatively short times calculated for their exposure before being buried by their respective overlying tephras (members (e) and (b_2)).

Because acidic volcanism is paroxysmal rather than "accretionary" it is possible to analyse and determine P.I.s on fresh and weathered lapilli and blocks of every eruptive episode. This provides distinct advantages over the method of Ruxton (1968a), who in determining rates of weathering of nine Papua ashes, assumed a constant chemical composition for initial eruptives and no post-depositional contamination.

P.I. is considered to be superior to other measures of weathering described by Ruxton (1968a,b), as it is a more rigorous estimate of the theoretical weathering potential of silicate rocks. Since precipitation primarily determines the rate of weathering of tephra (Ruxton 1968a, Bockheim <u>et al</u> 1969 and Hay and Blair 1972) it is considered that the index is valid in all situations where hydrolysis is the main cause of silicate weathering.

C. CAUSES OF VARIATION IN TITANOMAGNETITE COMPOSITION

Introduction

The term "oxide minerals" as used here refers to opaque minerals of the $FeO-Fe_2O_3-TiO_2$ system (Fig 19). Ti can enter the magnetite structure in considerable amounts, there being a continuous relationship between magnetite and the ulvospinel molecule ($Fe_2 TiO_4$). The term titanomagnetite is thus best restricted to specimens where an ulvospinel phase can be demonstrated.

Magnetite is an inverse spinel and its structure can be written (after Deer, Howie and Zussman 1961) as:

$8R^{3+}$	in four-fold coordination
$8R^{2+} + 8R^{3+}$	in six-fold coordination

or as $Fe^{3+}(Fe^{2+}. Fe^{3+})O_4$

Burns and Fyfe (1964) have shown that by subtraction of the crystal field stabilisation energies (CFSE) for tetrahedral sites (in the magma) from CFSE for octahedral sites (in the crystal) a value for the "site preference energy" for an octahedral site may be obtained for any transition element. The magnitude of the octahedral "site preference energy" determines the order in which the elements can be incorporated into minerals which crystallised from a magma with octahedral and tetrahedral sites. Ionic radius and charge also affect cation distribution within oxide minerals.

Of the elements examined in titanomagnetites (by optical emission spectroscopy and electron microprobe)

Cr, V and Al	substitute for Fe^{3+}, and
Co, Ni, Mn, Mg, Zn and Cu	substitute for Fe^{2+}.

Ca is present in inclusions of apatite crystals and to a lesser extent in silicates (Wright and Lovering 1965, Ewart 1967b and Cescas et al 1970). In samples analysed by optical emission spectroscopy, silicate inclusions increase Mg, Si and Al contents (p. 76). Zr is present only in inclusions of zircon crystals. The apparent mobility of Zr in titanomagnetite samples from peat swamps (e.g. Nos. 35-37, 94-96, 118, 119) is in accord with findings of Glagoleva (1970) who showed

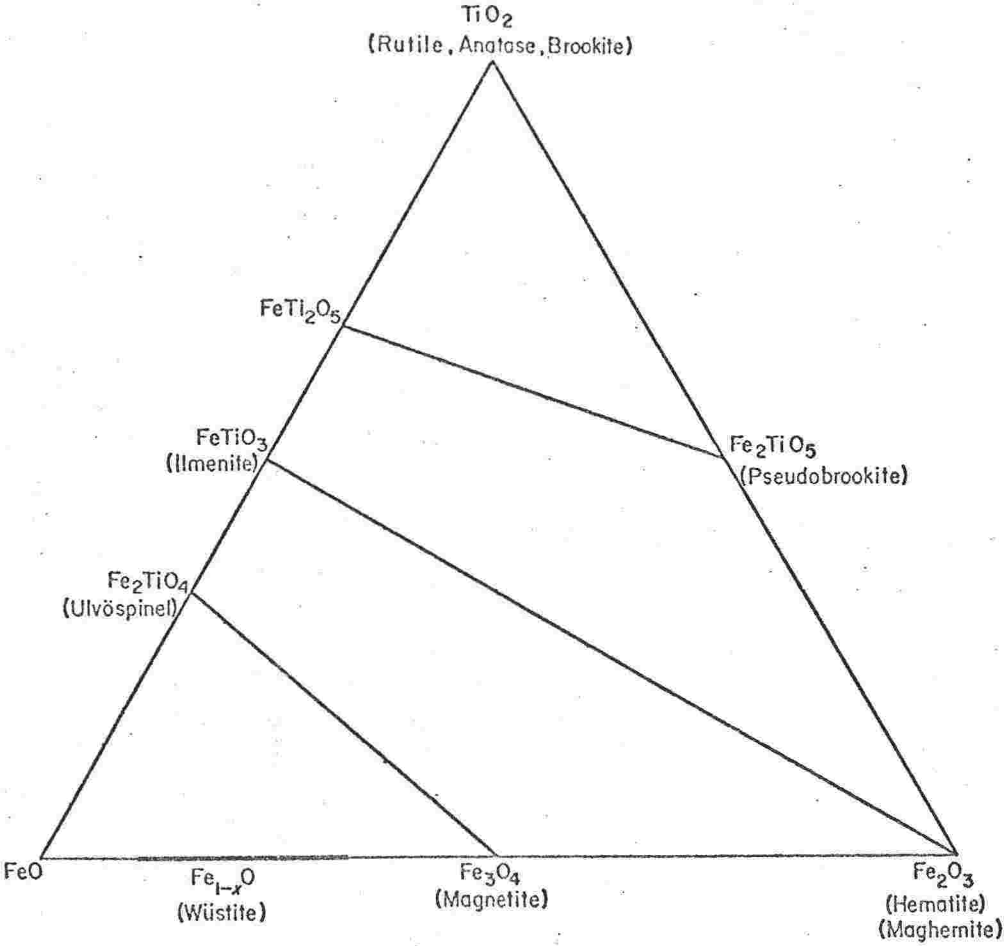

Fig. 19. - Phases in the system $FeO-Fe_2O_3-TiO_2$, showing the major solid solution series, magnetite-ulvospinel, hematite-ilmenite and pseudobrookite-$FeTi_2O_5$. Mole per cent. (after Buddington and Lindsley 1964).

that Zr from sediments and zircon grains, acquired some mobility in an acid environment.

In titanomagnetites, generally, with increasing temperature and more basic magma composition, Mg, V, Cr, Co and Ni contents increase and Mn decreases (see Tables 2, 17, 19, 23 and Appendix IV, Table 2).

A Comparison of Bulk and Microprobe Analytical Methods

Titanomagnetites analysed often include grains which contain variable amounts of hematite-ilmenite lamellae produced by progressive oxidation of the homogeneous grains (Wright and Lovering 1965). The same writers have also shown that with the compositional changes accompanying oxidation, there is no need to invoke bulk compositional variation within a given sample. Because Tsg 19 contained lower Ti than any other Tsg titanomagnetite analysed Ewart (1967b) suggested that during crushing and separation many of the oxidised rhombohedral phases (titanohematite) were removed. Tsg 19 has now been shown to be andesitic (with lower Ti) and thus there is no need to suggest that any crystal inhomogeneities within titanomagnetites have been removed during purification and concentration of samples.

However, during electron microprobe analysis inhomogeneous grains must be avoided as shown by relative enrichment and depletion of elements within different phases within grains (Wright and Lovering 1965). A large number of homogeneous grains must be examined in order to assess amount of contaminants (e.g. p. 76) and detect any possible differences in composition between titanomagnetite grains enclosed within different crystals. Electron-microprobe analyses of titanomagnetite phenocrysts from Oruanui Formation enclosed by glass and hypersthene are similar in composition (Tables 15, 20). The main advantage of electron microprobe studies is that inclusions and other contaminants can be avoided. Titanomagnetite contents of Ni, Co, Cr, Zr and Cu, however, are often below the detection limits of most microprobe analysers.

The use of bulk analyses and single grain analysis of titanomagnetites for tephra identification are thus complementary.

Distribution of Elements Between Fe-Ti Oxides

In the rhyolites studied, spinel (titanomagnetite) or rhombohedral (ilmenite) phases are usually enclosed in a ferromagnesian silicate, illustrating that oxide phases were first to crystallize. Thus, variations in element content of the oxide phases may be due either to different initial compositions of magma (i.e. availability of a particular element) or to titanomagnetite and ilmenite competing for elements in individual liquids. Carmichael (1967) has shown that generally titanomagnetite is relatively enriched in Al, Cr, V, Zn and Si and depleted in Mg and Mn relative to coexisting ilmenite. Ni and Co are also generally more abundant in titanomagnetites than coexisting ilmenites (Duschesne 1972). As the Fe-Ti oxides in acidic rocks from Taupo Volcanic Zone show, these trends (Ewart <u>et al</u> 1971), with two exceptions, it is probable that initial composition is more important in determining relative elemental abundances. The two exceptions are from younger Tsg members (Waimihia and Taupo Formations) where V in ilmenite is $\geqslant$ that for titanomagnetite. The proportions of the two oxide minerals in these samples is not known, but in most samples studied Fe-Ti oxides comprise <1% of the total rock with the amount of titanomagnetite greatly exceeding the ilmenite content.

Statistical studies of crystal abundances (Ewart 1967a) have shown that phenocrysts crystallized without any significant loss or gain by such processes as crystal settling. The systematic distribution of elements between coexisting minerals, and between minerals and coexisting glass have shown that minerals crystallised in the magmas in which they are found and are not xenocrysts (Ewart and Taylor 1969). In order to show that titanomagnetites are dominantly phenocrysts, and that minor amounts of xenocryst contaminants do not appreciably affect bulk analyses, titanomagnetite was extracted and analysed from the same rocks studied by Ewart and Taylor. Results are given in Table 18.

SAMPLE NO.	NAME AND LOCALITY	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
*P29205	K-Trig Basalt	N94/499406	7.22	1.35	0.24	1.72	3082	1655	134	229	451	132
P29166	Mt. Edgecumbe - andesite	N77/185088	8.06	1.63	0.46	1.16	6950	571	126	173	86	-
P29171	Maungaongaonga Dacite	N85/803814	8.64	0.76	0.78	0.20	2308	106	115	77	195	68
P28840	Taupo Pumice (Tsg 3) - Taupo Pumice pit.	N94/589347	7.92	1.06	0.69	0.54	649	131	16	27	68	22
P28854	Waimihia Lapilli (Tsg 15) as above	N94/587347	7.28	1.23	0.79	0.67	699	149	24	27	332	41
P29564	Ngongotaha Dome	N76/672074	5.84	0.38	0.57	0.15	1039	81	61	38	145	42
P29171	Rotoma Rhyolite Complex, Whakapoungakau	N76/763163	5.03	0.49	0.40	-	1804	112	69	76	346	61
P27854	Mokai Ring Structure rhyolite	N93/353584	-	0.24	0.51	0.13	1549	36	78	40	1236	-
P27576	Haroharo Rhyolite Complex, Lake Rotoiti	N76/899141	5.02	0.79	0.72	0.26	1130	59	76	30	1246	39
P27575	Haroharo Rhyolite Complex, Lake Rotoiti	N77/941140	5.27	0.73	0.74	0.37	1694	100	103	45	750	51
P27580	Haroharo Rhyolite Complex, W end Lake Rotoma	N77/028161	5.45	0.60	0.60	0.12	1847	104	67	56	138	53
P27573	Rotoma Rhyolite Complex, Lake Rotoma	N77/043181	4.54	0.57	0.67	0.64	1701	110	82	64	551	40
P27853	Rhyolite lava at Aratiatia Damsite	N94/608462	7.52	0.43	0.81	0.17	727	101	121	54	149	87

*All samples belong to the petrological collection of the N.Z. Geological Survey.

- not determined.

Table 18. - Analyses of titanomagnetites from Taupo Volcanic Zone rocks which have been previously chemically analysed for whole rock, residual liquid or phenocryst contents (excluding titanomagnetite) by Ewart et al (1968a) and Ewart and Taylor (1969). Further analyses are given in Table 16 (Puketarata Dome) and Appendix V (Matahina, Whakamaru and Paeroa Ignimbrites). Information on analyses as for Table 6.

Compared to their coexisting hypersthenes the titanomagnetites have higher V, Cr, Co and Ni and lower Mg and Mn contents. Relative elemental distributions are also similar for coexisting augite except that titanomagnetites contain higher Mn. Titanomagnetites are enriched in V, Cr, Co, Ni and Mn and depleted in Mg relative to coexisting calcic-hornblende. The distribution of the elements between phases is predicted by crystal-field theory. The octahedral "site preference energies" of V and Cr exceed that of Fe^{3+} and similarly the divalent elements Ni and Co exceed that of Fe^{2+}, consequently the proportion of transition elements is greater in the earlier crystallizing titanomagnetite. Mn^{2+} has no octahedral "site preference energy" (Burns and Fyfe 1964) and its greater affinity for hypersthene maybe due to the large number of Mg^{2+} and Fe^{2+} sites available.

In Figs 20 and 21, V and Cr abundances in titanomagnetites are compared with those of coexisting hypersthene, hornblende and residual glass. A regular distribution of elements is strongly evident. Mg in titanomagnetites correlate well with Mg in coexisting residual glasses (Fig 22). Mn values for titanomagnetites plotted against Mn values for coexisting biotites (Ewart 1971a), and hypersthene and hornblende (Fig 22) again suggest that there is a systematic distribution of these elements between the various phases. Titanomagnetites analysed are therefore considered to be dominantly phenocrysts.

The variations in V content of residual liquid (Fig 20) is probably due to the very rapid uptake of V by phenocrystic titanomagnetite, and as the latter occurs in small modal quantities, slight variation in titanomagnetite between samples results in relatively significant variations of V in the groundmass (Ewart and Taylor 1969). Although only three samples were analysed, data in Fig 22 suggests that Mn uptake in biotite maybe largely controlled by amounts taken into the earlier crystallising titanomagnetite.

The limited data presented indicate that the general correlation between the titanomagnetite, ferromagnesian minerals, plagioclase and residual glass is largely controlled by the initial magma composition, although subsequent crystallization

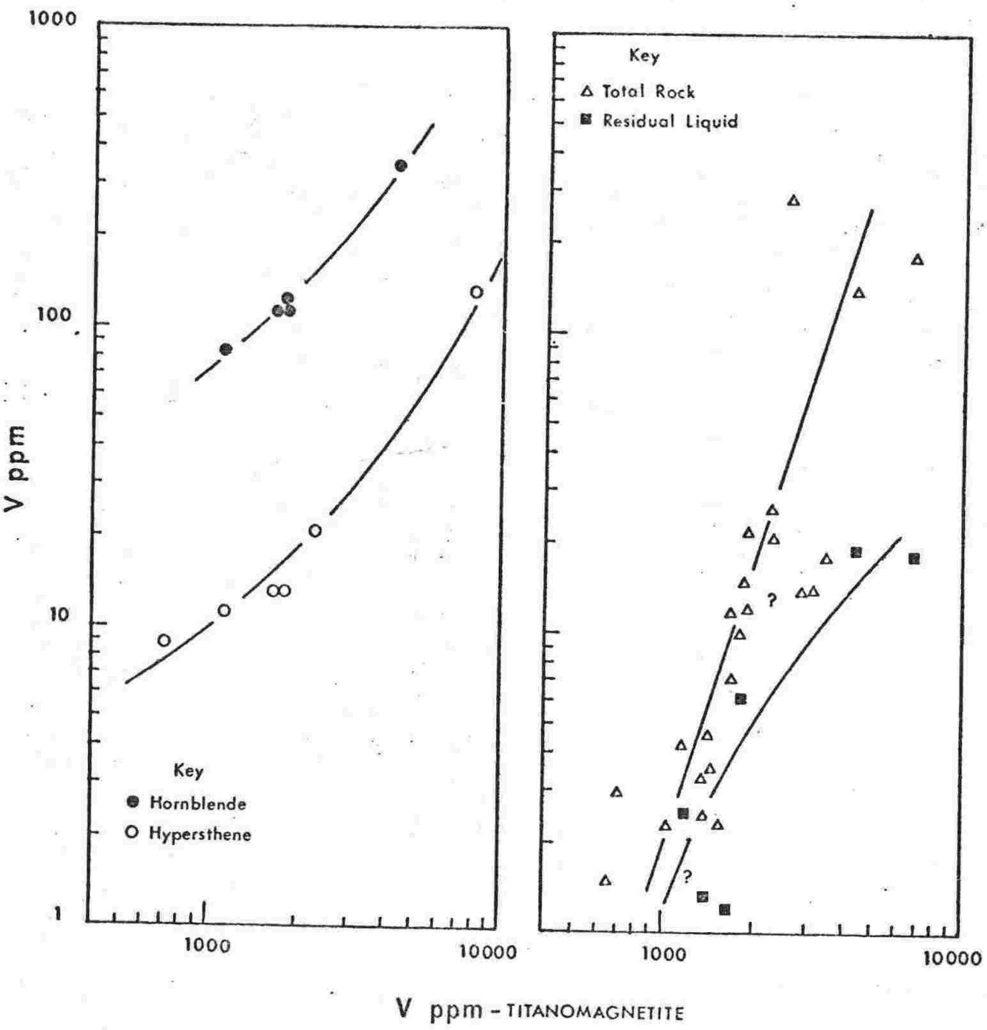

Fig. 20. - V concentrations of titanomagnetite phenocrysts plotted against the V concentrations of their respective coexisting, hypersthene and hornblende phenocrysts, and whole rock and groundmass compositions. Lines fitted through points are visual best fit estimates.

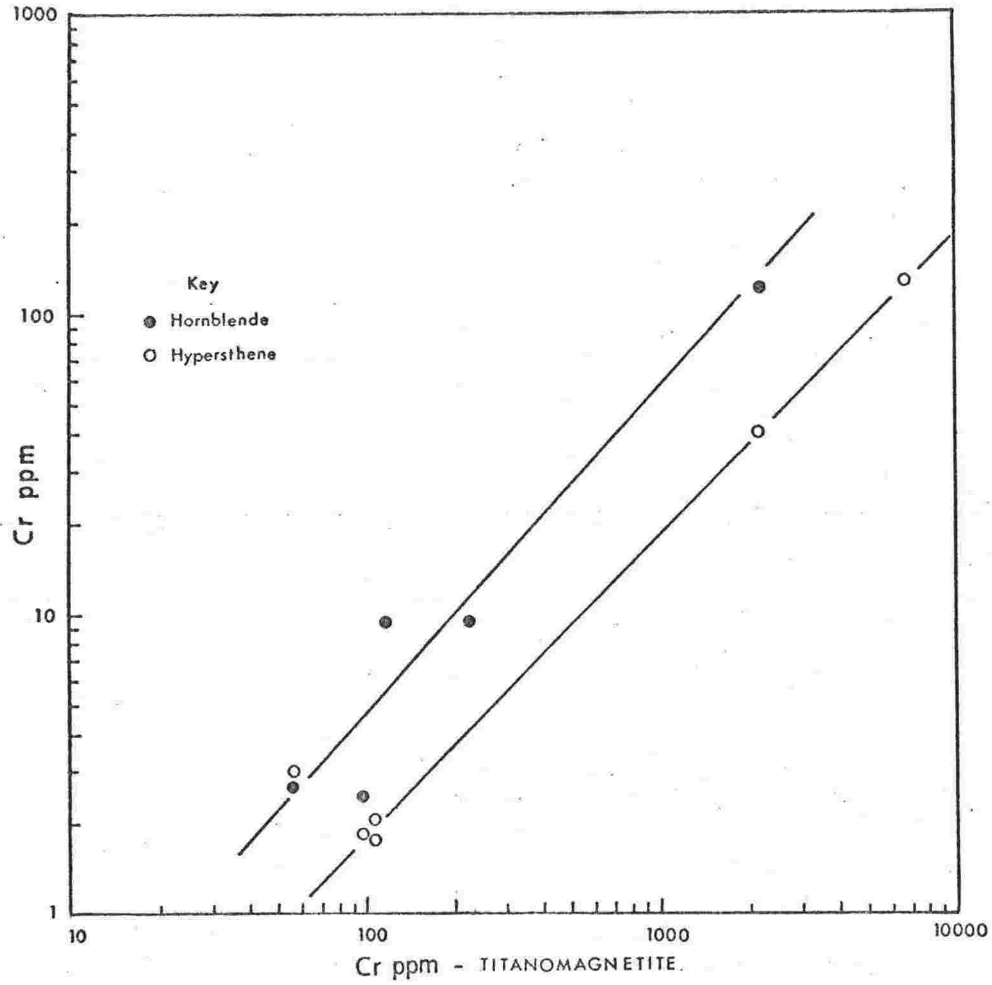

Fig. 21. - Cr concentrations of titanomagnetite phenocrysts plotted against the Cr concentrations of their respective coexisting hypersthene and hornblende phenocrysts. Lines fitted through points are visual best fit estimates.

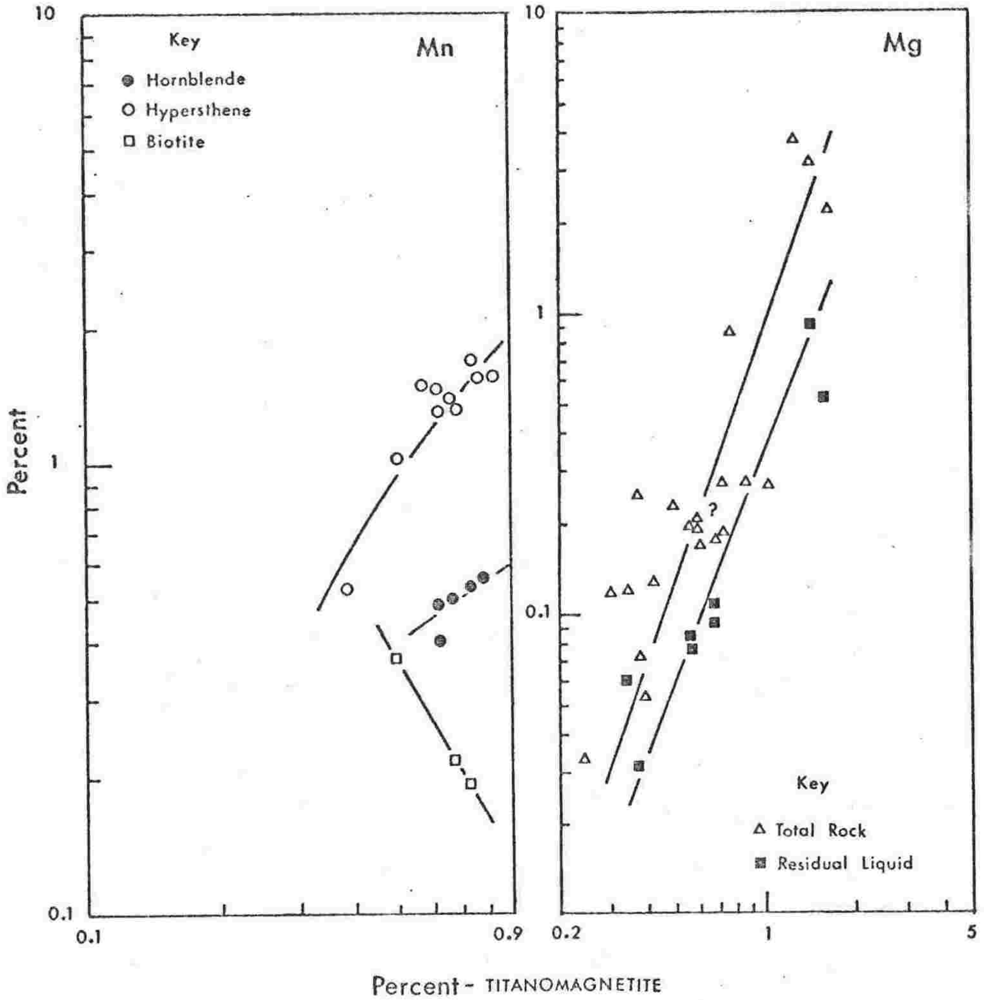

Fig. 22. - Mn concentrations of titanomagnetite phenocrysts plotted against the Mn concentrations of their respective coexisting hypersthene, hornblende and biotite phenocrysts. Mg concentrations of titanomagnetite phenocrysts are plotted against the Mg concentrations of their respective coexisting total rock and groundmasses. Lines fitted through points are visual best fit estimates.

of minerals also influences the residual glass composition.

Petrogenetic Effects on Titanomagnetite Variability

Variations in titanomagnetite composition caused by differences in petrogenetic histories of high Al basalts are shown in Tables 18 and 19. The aphyric Tarawera Basalt contains only groundmass titanomagnetite, the Tatua Basalt is porphyritic. Ongaroto Basalt is coarsely-porphyritic and is considered to be a cumulate rock (Cole 1973). The Matahi and Rotokawau Basalts contain small devitrified rhyolitic xenoliths which are difficult to separate. The titanomagnetite compositions agree with whole rock trends (Cole 1973) and also show a general Ti increase and more basic composition from north to south. Ongaroto titanomagnetite contains high V, Co and Ni and relatively high Cr compared to those of other basalts. The high abundances are consistent with the entry of these elements, having octahedral "site preference energies", in the early formed titanomagnetite of this cumulate rock. The titanomagnetites of basalts generally contain lower V, Cr, Co, Ni and Mg than those from Tongariro andesites (Table 17). This difference probably indicates that the basalt, thought to originate from the mantle (Cole 1973, was not derived by a single stage process. Differences in titanomagnetite composition and petrography of basalts indicate that basalt magma probably ascended faster to the surface in the northern Taupo Volcanic Zone.

In some of the rhyolites studied, particularly from lavas, oxidation may affect amphiboles and biotite, with extensive resorption and replacement by very fine-grained iron oxides. Although these alteration products are generally removed during separation, a sample from Wahanga Dome, containing primary titanomagnetite and abundant fine-grained iron oxide after biotite, was analysed (Table 16 No. 3). It was found to be similar in composition to other unoxidised rhyolite (Table 16 Nos. 1, 2 and 4).

The vertical changes in V content, previously noted in Kaharoa and Mangaone tephra (p. 101), are similar to trends noted in ash-flows by Lipman (1971). Mg and Al increase and

HIGH-AL BASALTS

SAMPLE NO.	NAME	LOCALITY	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
	Matahi	E bank Tarawera River, at Kawerau.	N77/161093	4.50	1.17	0.24	1.72	3283	179	152	112	162	41
*22993	Tatua	0.5 km N of Palmer Rd.	N94/562504	7.40	1.15	0.36	2.09	3400	20	109	145	400	-
22998	Ongaroto	Quarry, eastern flow.	N84/414732	9.02	1.36	0.36	0.90	5500	360	165	400	350	-
		ACIDIC LAVAS											
30007	Mt. Tauhara (Dacite)	Burrows Quarry.	N94/648384	5.32	1.90	0.49	1.79	2853	770	188	234	273	142
P29563	Rotorua Caldera rhyolite	Kawaha Point.	N76/713077	5.86	0.31	0.72	0.24	941	78	55	36	640	48
P29640	Lake Taupo Volcanic Centre, rhyolite		N93/432383	6.54	0.68	0.52	0.65	2185	198	67	80	259	23
	Maunganamu Dome, rhyolite		N94/596318	5.34	1.16	0.64	0.18	1911	178	125	145	127	-
	Motuopuhi Is. rhyolite	Lake Rotoaira	N112/198956	6.81	0.67	0.40	0.10	4335	461	92	161	94	71
	Kaharoa Granodiorite - Mt. Tarawera			3.93	0.19	1.23	0.60	1534	104	16	20	1458	20

*Sample Nos. prefixed by "P" belong to the petrological collection of the N.Z. Geological Survey. Numbers with no prefix belong to the petrological collection of the Geology Department, Victoria University.

- not determined.

Table 19. - Analyses of titanomagnetites from Taupo Volcanic Zone High-Al Basalts, selected acidic lavas and Kaharoa Granodiorite. Further analyses of High-Al Basalt titanomagnetites are given in Table 18 (K-Trig) and Appendix II (Tarawera, Rotokawau and Matahi). Information on analyses as for Table 6.

Mn decreases were also noted by Lipman accompanying the V increase, but these trends were not found in the titanomagnetites analysed. The upward change in elemental abundances was attributed by Lipman to lower temperatures of crystallisation and higher water content at the top of the magma chamber.

An analysis for titanomagnetite from a granodiorite associated with the Kaharoa eruption and considered to be comagmatic (Ewart and Cole 1967) is given in Table 19. The composition of the titanomagnetite showing markedly higher Mn and Zr and lower Ti, Mg, Co and Ni contents than the average Kaharoa titanomagnetite (Table 6) provides an insight into the end products of crystallization of associated rhyolites.

Iron - Titanium Oxide Equilibration Temperatures

Ewart *et al* (1971) have shown that 13 co-existing titanomagnetite and ilmenite pairs from Taupo Volcanic Zone acidic rocks give two groups of equilibration temperatures, 735°-780°C for amphibole-bearing rhyolites and 860°-890°C for young non-amphibole bearing pumices. The data also showed that there is no obvious correlation within the rhyolites between bulk chemical composition, mineralogy and Fe-Ti oxide equilibration temperatures, but that a correlation did exist between the presence or absence of quartz and sanidine phenocrysts, the equilibration temperatures and the residual glass.

The earlier erupted Tsg members have higher normative corundum and higher K contents compared to the later erupted pumices. These chemical differences were considered by Ewart *et al* (1971) to be due to early melting, of the Mesozoic eugeosynclinal "basement" sediment - Ewart and Stipp (1968), involving a relatively higher proportion of muscovite and biotite phases, whereas later magmas continued to develop by higher degrees of partial melting (in response to increasing temperature). This implies that the older magmas equilibrated at lower temperatures than the younger Taupo magmas and this is substantiated by the 820°-855°C oxide equilibration temperature for Karapiti Lapilli (Dr. C.P. Wood, N.Z. Geological Survey, pers. comm.) and 860°-890°C for younger Taupo magma (Ewart *et al* 1971).

In Okataina Volcanic Centre, the c. 44,000 yr B.P. Rotoiti Breccia Formation, oxide equilibration temperature was 740°C (Ewart et al 1971) while those for the youngest rhyolite from that centre - Kaharoa Tephra was 745°C (Table 20). Oxide equilibration temperatures of domes of varying ages in this centre ranged between 735°-780°C (Ewart et al 1971). Oruanui tephra erupted from a source in the vicinity of northern Lake Taupo had an oxide equilibration temperature of 780°-800°C (Table 20).

Although the older Taupo magma oxides equilibrated at slightly lower temperatures than the younger Taupo magmas, they both represent inherently high temperature magmas. It therefore seems probable that higher temperature magmas are not necessarily associated with younger eruptives but rather with the locality of their source. The evidence suggests a trend of increasing oxide equilibration temperatures from N-S within the Taupo Volcanic Zone. This increase may be connected with the proximity of andesites of the Tongariro region to the south.

Ni and Co Contents of Titanomagnetites

Rhyolitic titanomagnetites generally increase in Ti, V, Cr, Co and Ni, and decrease in Mn contents (note younger Taupo Sub-group tephras - Table 6 are exceptions here) from north to south, indicating a basic trend.

The changes in Ni and Co values between volcanic centres deserves special comment. Titanomagnetites analysed from Okataina Volcanic Centre tephras generally contain Co $\geqslant$ Ni. In tephras erupted from sources to the south Ni generally exceeds Co content. Mapara and Whakaipo Tephras in having approximately equal amounts of each element are exceptions here. Rhyolite lavas erupted from Okataina Volcanic Centre (Tables 16, 18 and 19) and centres to the south generally also show similar trends (Table 16 and 19).

The above finding is confirmed by the lack of Ni in hypersthenes from Okataina Volcanic Centre (Ewart and Taylor 1969). This being due to octahedral "site preference energies" favour-

Table 20. - Electron micro-probe analyses of iron-titanium oxides.

Samples 1,2,4 and 5 were analysed by the author with the electron microprobe of the N.Z. Geological Survey, using procedures described by Carmichael (1967). See Appendix I for operating details.

Dr. C.P. Wood analysed sample no. 3 and Mr. P.R. Kyle analysed sample nos. 6 and 7 (see Table 14 for operating conditions).

SAMPLE NO.	1	2	3	4	5	6	7
Spinel Phase							
%							
SiO_2	0.05	-	0.06	-	0.08	0.02	0.03
TiO_2	13.2	13.5	8.44	8.65	10.58	10.18	9.81
Al_2O_3	1.86	2.0	1.25	1.22	1.51	1.60	1.57
V_2O_3	0.08	0.08	0.11	0.09	0.55	0.30	0.28
Cr_2O_3	-	-	0.02	-	n.d.	0.02	-
FeO	78.46	78.60	83.19	83.70	81.30	82.36	82.96
MnO	0.88	0.85	1.09	1.11	0.62	0.52	0.49
MgO	0.92	0.82	0.41	0.43	0.59	0.75	0.70
ZnO	-	-	0.12	-	-	-	-
Sum	95.45	95.85	94.69	95.20	95.23	95.75	95.85
Recalculated analyses (Ulvospinel basis)							
Fe_2O_3	41.31	40.93	51.02	51.26	46.25	47.84	48.70
FeO	41.26	41.75	37.28	37.55	39.68	39.31	39.13
Total	99.56	99.93	99.80	100.31	99.86	100.54	100.72
Mol. % Usp.	37.50		24.29		30.28	28.71	27.70
$\overset{\circ}{a} \pm 0.002$	8.436		8.415		8.423	8.423	8.423
Rhombohedral Phase							
%							
SiO_2	-		-		n.d.	n.d.	n.d.
TiO_2	47.31		46.44		48.33	46.69	46.73
Al_2O_3	0.11		0.13		0.08	0.12	0.12
V_2O_3	n.d.		n.d.		n.d.	n.d.	n.d.
Cr_2O_3	n.d.		n.d.		n.d.	n.d.	n.d.
FeO	48.31		48.41		49.22	50.11	49.65
MnO	1.10		2.03		1.15	0.96	0.93
MgO	1.80		1.13		1.31	1.52	1.51
ZnO	-		0.02		-	-	-
Sum	98.64		98.16		100.09	99.40	98.94
Recalculated analyses (Ilmenite basis)							
Fe_2O_3	10.81		11.92		10.27	13.10	12.50
FeO	38.57		37.69		39.98	38.32	38.40
Total	99.70		99.36		101.12	100.72	100.19
Mol. % R_2O_3	10.39		11.54		9.71	12.46	11.95
Temp. °C	850		745		780	800	785
$-\log_{10} fO_2$ (atm.)	12.8		15.0		14.4	13.6	14.0

Key to sample nos.

1 *11843 Taupo Pumice (mem. 3) - spinel phase enclosed by glass.
2 " " " " " " " " hyperathene.
3 Kaharoa Ash (analysis no. 13 - Appendix II) - spinel phase, discrete grain.
4 " " (" " 16 - " ") - " " - enclosed by glass.
5 11877 Oruanui Ash - chalazoidites.
6 and 7 11875 "Yellow-Grey Tephra".

- not determined. n.d. not detected. Limits of detection: SiO_2, Cr_2O_3, V_2O_3 and ZnO - 0.02.
*Numbers refer to samples lodged in the petrological collection of the Geology Department, Victoria University.

ing incorporation of Ni rather than Co into early formed oxides, thus using up most of available Ni, but still leaving Co for incorporation into the many Mg^{2+} and Fe^{2+} sites available in the hypersthenes. The data also largely explain the general lack of Co and Ni in residual glasses (Ewart et al 1968a). To the south the more 'basic' titanomagnetites show higher Ni relative to Co, with hypersthene from Taupo Pumice and hornblende from Puketarata Dome showing relatively high Ni contents, and Co contents approximately the same as those from northern ferromagnesian minerals. The higher values of Ni relative to Co in Tongariro andesites (Table 17) again suggests that they may have "influenced" the composition of southern rhyolite magmas.

Titanomagnetite composition of Mt Tauhara dacite (Table 19), shows Ni $>$ Co, while those of Maungaongaonga dacite (Table 19) Mangaone Lapilli Formation dacites (Table 6) erupted from more northerly localities show Ni $<$ Co.

Regional Significance of Titanomagnetite Variations

The northern, lower-temperature rhyolites contain titanomagnetite of generally similar composition, with increases in V and Cr providing useful differences for tephra identification purposes. The reasons for the occurrence of slightly more "basic magmas" within Okataina Volcanic Centre may be due to inhomogeneities in the crustal material being melted. Alternately, Cole (1973) has drawn attention to the structural control of basaltic eruptive centres and suggested that they may have been controlled by major regional faults, especially where they intersect caldera structures. Rotorua Ash, Earthquake Flat Breccia Formation and Rotoiti Breccia Formation (all more basic in composition) are known to have been erupted from peripheral areas of Okataina Volcanic Centre and it is possible that the proximity of any basalt may have slightly affected the composition of the magma. If this was the case then as concluded by Ewart and Taylor (1969), any contamination or hybridisation processes which may have taken place were presumably essentially completed prior to the crystallization of the phenocrysts.

The southerly more 'basic' magmas could have been derived by either of the above processes, but it is probable that they have been "influenced" in composition by the Tongariro Region andesites. This has also been suggested from petrographical evidence from within Lake Taupo Volcanic Centre by Ewart (1966). Ewart et al (1971) suggested that the development of "higher temperature" Taupo Pumice magmas required the increasing involvment of less hydrous phases (e.g. hornblende) and developed by higher degrees of partial melting. If this hypothesis is correct, then the increasing involvement of andesites in petrogenesis of rhyolite magmas could have provided the higher temperatures required.

Finally, in attempting to explain mineralogical and chemical differences in rhyolitic tephras of Taupo Volcanic Zone it may be appropriate to develop the theme used by Turner (1970) in his presidential address to the Mineralogical Society of America, 11 November, 1969.

... "Every geological event, like every event in human history is unique. If we concentrate too heavily on discernment of order and pattern, may we perhaps overlook or underrate the unique quality of each igneous or metamorphic episode? Possibly uniqueness may have as great significance as conformity to pattern when we attempt to fit the phenomena of petrology into the broad framework of geology." ...

GENERAL CONCLUSIONS

1. Laboratory studies show that titanomagnetite chemistry, dominant ferromagnesian mineralogy and to a lesser extent, chemistry of unweathered pumice, together serve to identify most post 44,000 yr B.P. acidic tephras erupted from Taupo Volcanic Zone, New Zealand.

2. The occurrence of Ti, V and Cr in appreciable amounts and in a wide range of concentrations are the most useful elements in titanomagnetite for tephra identification.

3. The most useful ferromagnesian mineralogical criteria for tephra identification are the presence of abundant biotite and the dominance of amphibole over hypersthene.

4. Detailed work on glass chemistry is the next necessary step for tephra identification studies on Taupo Volcanic Zone acidic eruptives.

5. Fossil soils on tephra deposits may be contaminated, especially by andesitic tephra, and care must be taken in studying weathering or paleopedology of such paleosols.

6. The use of electron-microprobe and optical emission spectroscopy for analysis of titanomagnetite for tephra identification are complementary. Inclusions in grains can be avoided and contaminants can be individually detected, using electron-microprobe analysis. Bulk chemical analysis of titanomagnetite by optical emission spectroscopy, allows analysis of trace elements and also largely overcomes problems of crystal inhomogeneity due to oxidation.

7. In acidic eruptives studied, all the products of a volcanic episode (tephra and lava) generally have comparable titanomagnetite compositions, despite differing mechanisms of deposition.

8. The upward movement of andesite magma in Tongariro Region c. 10,000 yr B.P. may have provided the trigger for eruption of the oldest Taupo Sub-group rhyolitic tephras c. 9,800 yr B.P. After c. 8,850 yr B.P. andesitic volcanism had no signi-

ficant effect on the timing of rhyolitic tephra eruptions.

9. Limited data show that, Fe-Ti oxide equilibration temperatures increase, and titanomagnetites become more basic, in acidic eruptives from the southern part of Taupo Volcanic Zone. The trends probably indicate the increasing involvement of andesites of Tongariro Region in petrogenesis of the more southerly rhyolitic magmas.

PART 2

STUDIES OF PRE c. 44,000 yr B.P. PYROCLASTIC ROCKS ERUPTED FROM THE CENTRAL NORTH ISLAND, NEW ZEALAND

A. STUDIES OF TITANOMAGNETITE CHEMISTRY AND MINERALOGY OF NEW ZEALAND IGNIMBRITES

Introduction

Since Marshall (1932) first described ignimbrites in N.Z. much has been written about these eruptives in published works and unpublished New Zealand Geological Survey reports.

During the last 15 years much additional data has been obtained from site investigation holes for geothermal and hydroelectric power schemes and railway tunnels.

Aspects of ignimbrite stratigraphy and petrology have been published by Martin (1961, 1965), Blank (1965), Ewart and Healy (1965a, b, c, d), Ewart (1965b), Grindley (1965a, b, c) Bailey (1965), Healy (1969) and Lloyd (1972). A review of central North Island pyroclastic-flow deposits has been compiled by Briggs (1973). This study derives an identification scheme for most ignimbrites using ferromagnesian mineralogy and titanomagnetite chemistry, and uses the fission-track method to determine the sequence of volcanic events in the central North Island of N.Z.

The age relationships of ignimbrites studied are given in Fig 23.

Mineralogy

The mineralogy of most ignimbrites have been summarised by Martin (1961, 1965), Blank (1965), Ewart (1965a, b), Ewart and Healy (1965a, b, c, d), Ewart (1968), Healy (1969) and Lloyd (1972). Mineralogy does not vary markedly through most ignimbrites, although Ewart (1965a) and Martin (1965) have noted an upward increase in crystal content in the lowest sheet of Whakamaru Ignimbrite and the incoming of sanidine at the top of the same sheet. Healy (1969) described the incoming of biotite in the upper part of the Waiteariki Ignimbrite.

Most ignimbrites contain hypersthene as the dominant ferromagnesian mineral, often with traces of hornblende, bio-

AGE (x 10^6 yrs B.P.)	COROMANDEL REGION	CENTRAL VOLCANIC REGION KING COUNTRY (western area)	(central and eastern area)	AGE (x 10^6 yrs B.P.)
0.15			Kaingaroa Ignimbrite (N)*= Murupara Gorge Ignimbrite	0.15
			?Mamaku Ignimbrite (N)	
0.26			Matahina Ignimbrite (N)	0.26
0.30			Te Whaiti Ignimbrite (N) = Rangitaiki Ignimbrite (N)	0.30
0.31		Rocky Hill Ignimbrite (N)		0.31
0.33			Whakamaru Ignimbrite (N) = Manunui Ignimbrite (N)	0.33
			?Atiamuri Ignimbrite	
			?Waiotapu Ignimbrite (N)	
			?Wairakei Ignimbrite	
			Paeroa Ignimbrite	
			Te Weta Ignimbrite	
0.58			Te Kopia Ignimbrite (N)	0.58
0.63 0.64		Marshall Ignimbrite (N) Upper Ahuroa Ignimbrite (N)	/ ?Ranginui Ignimbrite	0.63 0.64
0.65		Lower Ahuroa Ignimbrite		0.65
0.69				0.69
		Waipari Ignimbrite		
0.75		Ongatiti Ignimbrite (R)		0.75
0.84	Waiteariki Ignimbrite (R) = Papamoa Ignimbrite	Crystal Lithic Lapilli Ignimbrite (R)	Rangitoto Ignimbrites (ages inferred)	0.84
0.86	Aongatete Ignimbrite	Ngaroma Lenticulite (R)		0.86
0.94	Aongatete Volcanics, lower tuffs and breccias	Pumice-Lapilli Ignimbrite (R)		0.94
1.50	"Tridymite Rhyolite"			1.50
2.89	Owharoaite (Wilsonite) (R)			2.89
**3.92	Waitawheta Dacite			**3.92
**4.01	Beeson's Island Volcanics			**4.01

* Magnetic polarity of ignimbrite (N) = normal, (R) = reversed. Most data from Cox (1969, 1971), data on Whakamaru Ignimbrite (Hatherton 1954). Data on polarity of Pakaumanu Ignimbrites (in King Country area), excluding Marshall Ignimbrite, determined in this study.

** K-A dates from Stipp (1968).

Fig. 23. - Stratigraphy and chronology of ignimbrites of central volcanic region. Ages are fission-track dates (unless otherwise indicated). Errors on fission-track dates are given in Table 22. Line at 0.69 m.y. B.P. indicates boundary between Brunhes epoch of normal polarity and Matuyama epoch of reversed polarity. ? = stratigraphic position inferred.

tite and augite. As with the younger tephras it is the presence of abundant biotite and the dominance of hornblende over hypersthene that are the most useful ferromagnesian mineralogical criteria for identification purposes. Sanidine also occurs in many biotite-bearing ignimbrites and the presence of this mineral, although not always persistent through sheets of the same ignimbrite (Ewart 1965a), may aid in correlation.

Chemistry

References to chemical analyses of ignimbrites have been summarised by Briggs (1973). Most unweathered ignimbrites are rhyolitic. The only exceptions are the Waitearaki and Papamoa Ignimbrites which are dacitic. The composition of the King Country Ignimbrites (Pakaumanu Group - Fig 23) is not well known and major element analyses of these ignimbrites given in Table 21 show them to be rhyolitic. Pumice Breccias (sample nos. 11919, 11924 and 11926) being relatively soft and pumiceous, are slightly more hydrated. Tuffs, (sample nos. 11918 and 11921) show this trend even more markedly. The lower Waipari Ignimbrite (No. 11922) and Ongatiti Ignimbrite (No. 11923) show little hydration and are considered to be slightly more basic than other Pakaumanu Group ignimbrites.

The use of bulk analyses for ignimbrite correlation is severely limited by: lateral sorting due to variable mineral density; addition of xenocrysts, mixing of pumice lumps, ash and phenocrysts of varied compositions (Lipman 1967, Walker 1972); and post-depositional changes which particularly affect alkali and halogen compositions (summarised by Scott 1966, 1971 a,b, Lipman 1967 and Ewart 1971b).

Because glass in ignimbrites is subject to post-depositional chemical changes and is commonly devitrified it is not useful for identification studies.

A limited number of major element analyses of ignimbrite phenocrysts are given in Ewart (1965a, 1966 and 1971b). Titanomagnetite and ilmenite analyses from Waitearaki and Manunui Ignimbrites are presented by Ewart et al (1971).

V.U.W. SAMPLE NO.	11915	11916	11917	11919	11920	11918	11921	11922	11923	11924	11926	11927
%												
SiO_2	70.39	70.42	70.41	67.99	70.78	49.58	58.54	68.78	69.44	68.37	68.29	70.94
Al_2O_3	16.18	15.07	14.50	16.22	15.05	26.23	20.56	15.28	15.48	16.31	16.82	15.33
*Fe_2O_3	2.57	2.78	2.86	3.80	3.75	5.28	5.04	3.73	3.77	4.08	4.18	3.10
Mg O	0.34	0.52	0.58	0.33	0.20	0.36	0.48	0.58	0.59	0.14	0.11	0.16
CaO	1.23	2.15	2.58	1.56	1.51	2.04	2.26	2.63	2.78	0.97	0.58	0.62
**Na_2O	2.43	4.04	4.60	4.37	4.29	2.52	3.87	4.78	5.30	3.37	2.17	3.28
K_2O	3.64	2.79	2.88	2.52	2.80	0.33	1.47	2.61	2.44	3.18	2.32	4.51
TiO_2	0.34	0.31	0.32	0.37	0.37	0.44	0.50.	0.37	0.38	0.36	0.40	0.32
P_2O_5	0.03	0.01	0.08	0.03	0.01	0.05	0.03	0.10	0.11	0.06	0.04	0.02
MnO	0.04	0.06	0.08	0.08	0.06	0.06	0.12	0.08	0.08	0.03	0.08	0.03
***LOI	3.37	2.93	1.99	3.68	2.15	12.72	6.41	1.98	0.59	3.75	5.54	2.51
TOTAL	100.56	101.08	100.88	100.95	100.97.	99.61	99.28	100.92	100.96	100.62	100.53	100.82

* Total Fe as Fe_2O_3

** Na_2O was analysed by atomic absorption spectrophotometry

*** Loss on ignition between 110° - 1000°C

Key to sample nos. (details of localities given in Appendix V)

11915	Rocky Hill Ignimbrite	
11916	" " "	(lower sheet)
11917	" " "	(upper ")
11919	Ahuroa Ignimbrite	(middle sheet)
11920	" "	(upper ")
11918	Tuffs - probable correlatives of younger sheets of Ahuroa Ignimbrite.	
11921	?Ahuroa Ignimbrite	(lower sheet)
11922	Waipari Ignimbrite	(upper sheet)
11923	Ongatiti "	
11924	Rangitoto Ignimbrites	(Crystal Lithic Lapilli Ignimbrite)
11926	" "	(Ngaroma Lenticulite)
11927	" "	(Pumice Lapilli Ignimbrite)

Table 21. - Major element analyses of pyroclastic rocks of the Pakaumanu Group (in the King Country area). Analyses were carried out by X-ray fluorescence (unless otherwise indicated). Details of sample localities are given in Appendix V.

Titanomagnetite Chemistry

Analyses of titanomagnetite from all pyroclastic-flow deposits studied are presented in Appendix V, with averaged analyses given in Table 23. A flow-sheet for identification of ignimbrites using titanomagnetite compositions in conjunction with dominant ferromagnesian assemblage is given in Fig 24.

From Appendix V and Table 23 the following points are evident:

1) The Mamaku Ignimbrite (erupted from Rotorua Caldera; Healy 1962), Pokopoko Breccia (underlying Mamaku Ignimbrite) and Matahina and Kaingaroa Ignimbrites (both erupted from Okataina Volcanic Centre; Healy 1962, Healy et al 1964, Bailey 1965) have similar titanomagnetite composition. This titanomagnetite composition is generally similar to that of many younger rhyolite tephras (Table 6) and lavas (Tables 16, 18) erupted from Okataina Volcanic Centre indicating that the magmatic composition in this area has changed little, over the past c. 260,000 yrs (Table 22).

2) The titanomagnetite data are consistent with the contention of Martin (1961 p. 472) that Te Whaiti Ignimbrite is probably a distal facies of Rangitaiki Ignimbrite. They are also consistent with the findings of Blank (1965 p. 600) who regarded the Manunui Ignimbrites as distal equivalents of Whakamaru Ignimbrite.

The generally similar titanomagnetite composition of these four ignimbrites together with the close relationship in time between their eruption (Fig 23 and Tables 22, 23) suggests that they may all be co-magmatic.

3) Titanomagnetite compositions are consistent with the provisional correlations; of Mamaku Ignimbrite with Orakonui Ignimbrite (Thompson 1966); of Ongatiti Ignimbrite with lower Waipari Ignimbrite (Blank 1965) (see also Table 21, Nos. 11922 and 11923), and Waiteariki Ignimbrite with Papamoa Ignimbrite (Healy 1963, Healy et al 1964).

FORMATION	No. of Analyses	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
Kaingaroa Ignimbrite	12	6.42±1.22	0.61± .20	0.69± .16	0.18± .17	1168±190	70±23	49±15	40±14	293±95	62±23
Mamaku Ignimbrite	9	7.62± .89	0.38± .10	0.89± .29	0.21± .09	1033±198	65±11	55±7	34±8	631±369	45±10
Pokopoko Breccia	4	7.12± .99	0.50± .18	0.70± .10	0.14± .02	1002±168	68±11	51±5	28±6	380±235	47±19
Matahina Ignimbrite	10	6.78±1.32	0.49± .10	0.79± .15	0.16± .08	1213±159	65±40	45±10	30±8	208±85	48±14
Atiamuri Ignimbrite	4	5.28± .46	0.36± .04	0.68± .08	0.05± .01	705±68	32±13	45±17	19±3	362±81	24±9
Orakonui Pumice Breccia	1	5.43	0.47	0.56	0.14	1290	31	59	38	802	35
Huka Pumice Breccia	1	7.37	0.66	1.08	0.06	2529	128	108	88	185	52
Rangitaiki Ignimbrite	9	6.74±1.11	0.73± .09	0.55± .08	0.71± .26	2892±304	226±23	83±4	120±33	206±73	46±18
Wairakei Ignimbrite	2	5.89± .04	1.27± .64	0.51± .06	1.67± .57	2665±49	331±206	90±4	124±26	190±35	77±15
Te Whaiti Ignimbrite	10	6.59± .84	0.72± .10	0.71± .15	0.68± .22	2475±344	233±25	77±13	84±10	385±97	45±19
Mamuni Ignimbrite	4	6.02± .21	0.56± .16	0.44± .07	0.19± .09	3046±508	203±41	101±27	113±28	98±39	37±11
Whakamaru Ignimbrite	16	6.26± .73	0.69± .23	0.62± .12	0.41± .42	2740±453	216±34	87±14	94±13	326±134	51±17
Paeroa Ignimbrite	5	5.49± .41	0.52± .19	0.82± .11	0.15± .07	1882±479	137±33	71±16	54±20	233±69	50±11
Te Weta Ignimbrite	5	4.83± .77	0.48± .13	0.75± .13	0.16± .12	1698±161	102±15	42±7	54±27	128±45	59±13
Te Kopia Ignimbrite	8	5.50± .43	0.57± .06	0.48± .08	0.19± .10	3357±366	197±17	103±12	109±7	94±17	59±23
Waiotapu Ignimbrite	8	8.08± .77	0.39± .09	0.89± .21	0.16± .17	1343±360	62±18	54±22	41±11	293±185	47±23
Marshall Ignimbrite	4	11.36±1.85	0.29± .15	1.73± .68	0.15± .04	1039±68	84±9	73±17	45±11	561±269	54±15
Ohakuri Pumice Breccia	6	6.52± .18	0.48± .04	0.74± .14	0.09± .03	1518±108	44±3	72±19	49±6	217±147	40±10
Rocky Hill Ignimbrite	6	6.17± .63	0.49± .17	0.45± .12	0.26± .25	2836±434	233±36	77±19	87±17	327±295	67±34
Ahuroa Ignimbrite (upper & middle sheets)	9	11.39±1.55	0.33± .12	1.01± .21	0.17± .03	658±256	64±17	56±11	30±9	549±376	73±10
Ahuroa Ignimbrite (?lower sheet)	3	7.46± .16	0.47± .11	0.55± .05	0.13± .06	3117±84	224±53	124±36	98±9	148±49	61±9
Waipari Ignimbrite	5	6.81± .38	0.46± .07	0.50± .06	0.19± .06	2963±157	175±11	84±3	94±8	109±25	43±13

FORMATION	No. of Analyses	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
Ongatiti Ignimbrite	11	6.97± .55	0.39± .10	0.49± .05	0.16± .07	2900±271	181±20	76±8	96±12	106±62	46±17
Rangimui Ignimbrite	2	11.13± .23	0.41± .08	1.10± .05	0.18± .02	541±72	61±6	71±1	41±3	245±17	64±8
Rangitoto Ignimbrites	8										
Crystal-Lithic-Lapilli Ignimbrite	4	10.14± .87	0.35± .05	0.62± .10	0.16± .03	1472±180	165±36	66±5	53±4	229±34	73±24
Ngaroma Lenticulite	2	7.20± .41	0.42± .09	0.53± .04	0.19± .11	2808±311	161±6	75±9	83±1	96±15	50±14
Pumice-Lapilli Ignimbrite	2	10.77± .18	1.02± .18	0.49± .10	0.17± .01	4579±374	391±10	127±21	189±14	428±213	71±9
Waitetariki Ignimbrite	11	6.57± .69	0.40± .08	0.34± .07	0.29± .21	4806±779	470±74	97±17	181±33	163±95	75±25
Papanoa Ignimbrite	2	7.81±1.06	0.62± .06	0.39± .04	0.14± .01	5045±146	399±132	89±5	164±14	101±8	74±35
Aongatete Volcanics	11										
Upper Tuffs and Breccias	2	8.57±1.01	0.78± .14	0.39± .07	0.36± .20	5233±329	1603±105	282±42	293± 41	167±69	163±13
Aongatete Ignimbrite	9	9.47±1.91	1.20± .58	0.41± .13	0.60± .25	1357±280	222±94	72±15	87±26	253±138	119±65
"Tridymite Rhyolite"	4	10.43± .75	0.27± .05	0.31± .08	0.36± .26	545±234	64±10	101±45	241±109	190±127	-
Wilsonite (Owharoaite)	5	7.91± .69	0.35± .06	0.28± .03	0.12± .03	3565±212	400±108	91±16	152±18	137±53	82±29

Table 23. - Averaged titanomagnetite analyses (± 1 s.d.) of > 44,000 yr B.P. central North Island pyroclastic-flow deposits. A complete list of analyses is given in Appendix V. Where only two samples have been analysed from a deposit then the ± is a mean deviation and not 1 s.d. Formations are not necessarily listed in stratigraphic order. Information on analyses as for Table 6.

4) The three ignimbrites forming the Rangitoto Ignimbrites of Blank (1965) all contain different titanomagnetite compositions and should be regarded as separate formations. The data also indicate that the distinctive Ranginui Ignimbrite has a different titanomagnetite composition from that of Ngaroma Lenticulite making the correlation between these two ignimbrites, tentatively suggested by Blank (1965), unlikely. A sample of ignimbrite resting on greywacke on the western side of the Otu-ao-roa Plateau (No. 512) has different titanomagnetite composition from Ngaroma Lenticulite with which it was previously correlated (Blank 1965).

5) Despite the major element and mineralogical changes described within the Whakamaru Ignimbrite by Ewart (1965a) and Martin (1965), titanomagnetites in this ignimbrite and in all others except for the Mamaku and Rocky Hill Ignimbrites (see below) do not show any vertical variations (see Appendix V, for Matahina Ignimbrite (*Nos. 372-76), Rangitaiki Ignimbrite (391-95), Te Whaiti Ignimbrite (402-7), Whakamaru Ignimbrite (418-21) and Waiteariki Ignimbrite (515-19).

6) Two titanomagnetite analyses from the upper Mamaku Ignimbrite (Nos. 356, 357) show marked enrichment in Mn and Ca and marked depletion in Ti, Mg, V, Cr and Ni compared with titanomagnetites in lower sheets. Two titanomagnetites analysed from the lower sheet of Rocky Hill Ignimbrite (Nos. 474, 475) show marked depletion of Mn, V, Cr and Ni compared with No. 473 from the same sheet which shows similar titanomagnetite composition to other Rocky Hill Ignimbrite samples.

Magnetites depleted in Ti, V, Cr and Ni are typical of those sampled from contact-metasomatic and hydrothermal deposits (Borisenko et al 1969). Ovchinnikov (1963), has proved experimentally that large amounts of Ti, V, Cr and Ni can be extracted from granite by steam, and the depletion of elements in magnetites from Mamaku and Rocky Hill Ignimbrites is attributed to alteration by intense vapour phase activity within parts of these ignimbrites following their deposition.

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* All nos. in this part refer to titanomagnetite analysis nos. in Appendix V.

Depletion of elements in titanomagnetites has not been noted in any other ignimbrites despite the "pink colours" of many handspecimens from which samples were extracted.

7) Titanomagnetites from older weathered tephra (Table 21 11918 and 11921 - Appendix V Nos. 484 and 486), as with those sampled from < 44,000 yr B.P. weathered tephra (Table 4 and Appendix II), do not show any significant differences from titanomagnetites sampled from fresh rocks of the same formation.

Examination of titanomagnetites from ignimbrites by electron microprobe shows that many grains are oxidised and a large number may have to be examined before finding any that are unmixed. The best part of ignimbrite sheets to sample for unoxidised grains of titanomagnetite is the basal welded vitrophyre layer, and this horizon also often contains fresh glass suitable for fission-track dating.

The differences in titanomagnetite composition show similar regional trends to those from younger tephras (p. 145). Kaingaroa, Matahina, Mamaku and Waiotapu Ignimbrites, all known to have been erupted from northern areas of Taupo Volcanic Zone, show Co $\geqslant$ Ni while Whakamaru, Rangitaiki and Ongatiti Ignimbrites erupted from more southerly localities show Ni > Co.

The age of the oldest andesite dated in Tongariro Region is 0.259±0.003 m.y. B.P. (K-A date Stipp 1968) so it is not known what influence andesite may have had on the composition of ignimbrites with sources to the south, all of which are older than 0.259 m.y. B.P. (see Fig 23). A lesser influence of andesite on the titanomagnetite composition of these ignimbrites maybe indicated by the relatively low Fe-Ti oxide equilibration temperature of 750°C reported for Manunui Ignimbrite (probably erupted from Lake Taupo Volcanic Centre) by Ewart *et al* 1971.

B. DATING OF N.Z. IGNIMBRITES

Grindley (1960), Martin (1961), Healy et al (1964), Blank (1965) and Healy (1969) have between them identified 24 major ignimbrites in central North Island. Twenty were considered to be Pleistocene and the other four were provisionally assigned to the Pliocene.

The first appearance of pumice considered to have come from central North Island was noted by Kear (1957) in oldest Pleistocene strata in south Auckland. The Plio-Pleistocene boundary in N.Z. is assigned an age of 1.79 m.y. B.P. (Kennett et al 1971), thus early estimates on commencement of rhyolitic volcanism in Taupo Volcanic Zone indicated it began slightly earlier than this date.

More recent evidence, however, suggests that known ignimbrites are much younger.

Ninkovich (1968) identified five widely spread ash horizons in deep-sea cores taken east of N.Z. and paleomagnetic dating showed these to range in age from 0.27 to 0.86 m.y. B.P. No older ashes were found though the sediments penetrated had a maximum age of approximately 3 m.y. B.P. Ninkovich considered that the distribution pattern indicated that they were erupted from N.Z. and that they are distal windborne tephra-fall associated with some of the large ignimbrite eruptions from Taupo Volcanic Zone.

More recently Cox (1969, 1971) has published paleomagnetic results carried out on nine of the ignimbrites mapped as Pleistocene and two mapped as Pliocene.

All ignimbrites considered to have been erupted from Taupo Volcanic Zone have normal polarity and were considered by Cox to be $<$ 0.69 m.y. B.P. Only Waiteariki Ignimbrite considered to have been erupted from Coromandel area (Fig 1) has reversed polarity and was considered to have been erupted during the Matuyama epoch of reversed polarity (Cox 1969). The boundary separating the two epochs was placed between the Te Kopia and Waiteariki Ignimbrites with little time separating the two units. The results of Cox thus generally agree with those of Ninkovich.

K-Ar dating of N.Z. Cenozoic volcanic rocks was carried out by Stipp (1968), but only two rhyolites from Taupo Volcanic Zone were dated, as most rhyolites examined were devitrified. The two samples dated are a lava from older rhyolites on the margin of the Mokai Ring Structure 0.219±0.01 m.y. B.P., and a fission-track date of 0.095±0.015 m.y. B.P. and K-Ar date of 0.11±0.01 m.y. B.P. on an obsidian from NW Lake Taupo area. The first date provides a minimum age for the first stage ignimbrites originating from Mokai Ring Structure.

Fission-Track Dating

The development of the fission-track method (Fleischer and Price 1964a, Fleischer and Hart 1972) offers the geologist a new inexpensive tool for dating minerals and glasses, and for determining their uranium contents.

Heavy, energetic particles from the spontaneous fission of ^{238}U create single narrow, but detectable trails of intense damage in the host mineral. These fission trails are displayed by preferential attack by a suitable chemical reagent (Fleischer and Price 1964a, Fleischer and Hart 1972) which allows the fission-track etch pits to be viewed and counted under an optical microscope. From the number of fission-tracks and a knowledge of the uranium content in a unit area of the sample, the time required to produce this number of tracks can be calculated.

This dating technique was used to determine the age of glass shards and obsidian from central North Island acidic rocks.

Technique Ignimbrite, sampled from a near-base vitrophyre, or distal deposits (crushed in a Tema-mill for 8-10 seconds), or from loose tephra was wet sieved, and the 2-4 phi fraction was dried at 60°C. Fresh glass shards were then concentrated by means of a Frantz Isodynamic Separator, each sample requiring different settings for purification. Approximately 70 milligrams of the glass, wrapped in aluminium foil, was placed in an aluminium can adjacent to two glass standards of known uranium content, properly calibrated for the purpose of monitoring neutron flux. The standards used were a glass used by Kleeman and Lovering (1970) and the U.S. National Bureau of Standards - SRM 614 1 ppm uranium glass used by Carpenter (1972). Each glass standard was sandwiched in Lexan plastic and wrapped in aluminium foil. Cans containing glass standards and samples were irradiated in the HIFAR nuclear reactor of the Australian Atomic Energy Commission at Lucas Heights, near Sydney, Australia.

The Lexan plastic acts as a solid state track detector and records the tracks caused by the thermal-neutron induced fission of ^{235}U in the glass standards. After irradiation, the Lexan plastic detectors were etched in 6N NaOH for 10 minutes at 70°C, or glass standards were etched for 20 seconds in 48% HF at 23°C. The neutron dose was calculated by counting the induced fission-track density in Lexan or glass standards with an optical microscope at x 450 magnification, using an eyepiece with a calibrated square frame. Lexan and glass standards were viewed under reflected light with the former being viewed under oblique lighting. No vertical flux gradient was detected.

Irradiated and non-irradiated glass shards were then placed in separate teflon moulds and mounted in an embedding resin (EPIGLASS or EPOFIX) and polished to an optical finish. Polished, mounted glass shards were then etched under identical conditions in 48% HF at 23°C, and then neutralised in concentrated ammonia solution (etching times are given in Table 22). Spontaneous and induced fission-tracks (Figs 25, 26) in glass shards were then point-counted under an optical microscope at x 450 magnification, using reflected light.

All counting surfaces are considered to be internal surfaces. That is a surface away from the original outer surface by more than the total effective range of fission tracks in the glass (i.e. approx. 12 microns). The etched fission-tracks observed thus result from fissions that occurred both above and below the counting surface.

Generally, at least 0.4 cm^2 of glass surface area was counted, but in the case of fime-grained or very pumiceous

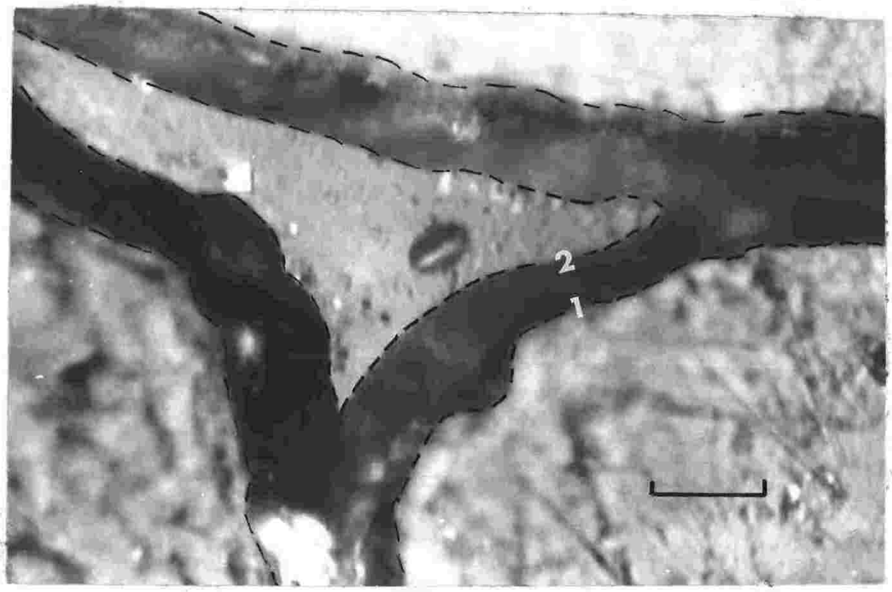

Fig. 25. - Single spontaneous fission-track in a glass shard from sample P29834-Te Whaiti Ignimbrite. 1-indicates extent of polished surface of shard prior to etching. 2-outlines polished surface after a 15 second etch in 48% HF at 23°C. Bar scale is 10 microns across.

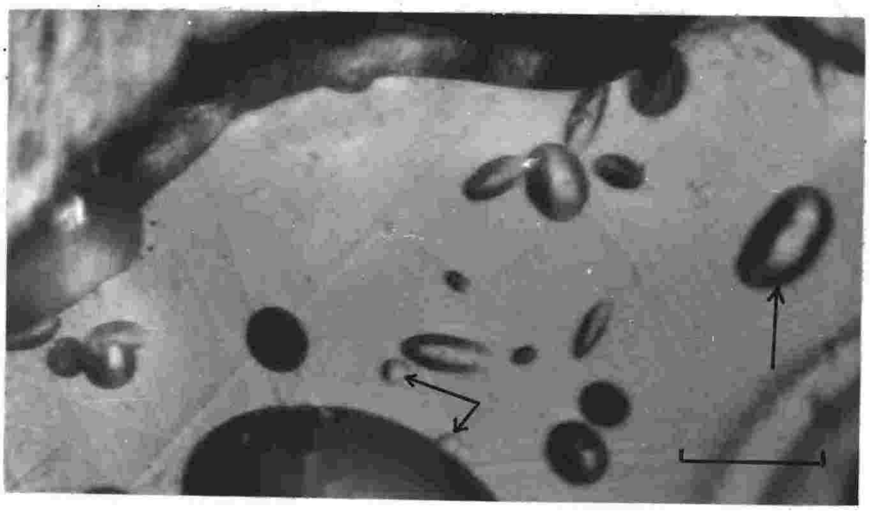

Fig. 26. - Neutron-induced fission-tracks in a glass shard from sample 10783-Ongatiti Ignimbrite. Arrows point to bubbles. Bar scale is 20 microns across.

shards the area counted was smaller because many shards are destroyed by etching. This results in a longer counting time (up to about 30 hours against 10-15 hours for large flat shards and 4-5 hours for obsidian) and larger errors on dates (providing uranium contents are comparable to coarser-grade samples).

The age determination equation (Fleischer and Price 1964a, Naeser 1967) reduces to:

$$\text{Age} = (\rho_s/\rho_i).\ 6.168 \times 10^{-8}.\ n$$

where ρ_s and ρ_i are the natural and induced fission-tracks per unit area and n = time-integrated flux of neutrons. In all cases the value used for the decay constant for spontaneous fission of ^{238}U was $\lambda_f = 6.85 \pm 0.2\ .\ 10^{-17} yr^{-1}$ (Fleischer and Price 1964b, Kleeman and Lovering 1971).

<u>Factors Affecting Accuracy and Precision of Dates</u> Sample imperfections e.g. bubbles and scratches can sometimes be confused with fission-tracks (which typically have a pin-pointed cone-like appearance). Therefore in the early stages of this study independent counts were carried out by Mrs D. Seward with whom the methods for dating described here were jointly derived. Counts carried out by Seward were within the error based on counting statistics of those derived by the author.

All glasses studied are considered to be unaffected by other factors which can affect accuracy, such as, relocation or migration of uranium (e.g. devitrified glass contains only 20-60% of uranium of fresh coexisting glass - Rosholt and Noble 1969) or annealing of tracks through heat or weathering.

The precision expressed for dates given in Table 22 was calculated from the sum of the errors determined from the number of spontaneous and induced tracks counted, and on errors involved in determining neutron dose. Uncertainties in the exact value of the spontaneous fission decay constant used were not considered.

<u>Ignimbrite Glass</u> Martin (1963) analysed two samples of pumice (Table 24) from Murupara Gorge Ignimbrite (here correlated with Kaingaroa Ignimbrite, <u>see</u> Table 22). According to Martin

and Lewis (1963) these analyses, plus refractive indices of glass indicated that the ignimbrite was composed of intermingled acid and intermediate glass shards and pumice. Although only pumice had been analysed, discrete, colourless and brown shards, were also considered to be rhyolitic and andesitic respectively, however, some tended to be composite with no distinct boundary between the two types. It was therefore postulated by Martin and Lewis that the shards were produced by the simultaneous pyroclastic eruption of acid and intermediate magmas.

In some other ignimbrites examined (e.g. Marshall, Whakamaru and Ongatiti Ignimbrites) lighter and darker coloured shards with composite types were also found. If the shards represent two contrasting compositions, and therefore contain different uranium contents (see Ewart and Stipp 1968 for typical uranium contents of rhyolites and andesites) then any fission-track dates determined on these mixed glasses would be meaningless.

The two types of glass shard were magnetically separated from a sample of Murupara Gorge Ignimbrite (10780 collected by Martin), and analysed for major elements. The analyses given in Table 24 show that the different fractions show some chemical differences, but both are rhyolitic in composition. The lighter coloured glass contains more SiO_2 and less MgO and total Fe than the darker glass.

The chemistry therefore shows that although there may be rhyolitic and andesitic pumice in Kaingaroa Ignimbrite (it being well known that this ignimbrite contains abundant andesitic fragments, Martin 1961, p. 474), light and dark glass shards (designated rhyolitic and andesitic by Martin 1963, plate 5, p. 57) are in fact all rhyolitic.

The cause of differences in glass shard colour is probably due in part to vapour phase activity.

Comparison of Fission-Track Dates with Previously Dated Samples

In order to check that the technique used was correct, the following previously dated samples were tested by the fission-track method.

Table 22. - Fission-track data and ages of some central North Island acid volcanic rocks.

The number of spontaneously produced tracks were subtracted from the total number of tracks after irradiation in order to obtain induced track density/cm^2.

The precision of dates was calculated from the sum of the errors determined, based upon the number of spontaneous and induced tracks counted, and on the errors involved in determining the neutron dose.

All samples were etched in 48% HF at 23°C.

Ages were calculated using the decay constant of $\lambda_f = 6.85 \times 10^{-17} yr^{-1}$.

*Numbers prefixed by "P" refer to samples in the N.Z. Geological Survey petrological collection. Numbers with no prefix are samples which belong to the petrological collection of the Geology Department, Victoria University. Details of all sample localities are given in Appendix V.

*SAMPLE NO.	FORMATION	ETCH TIME (secs.)	SPONTANEOUS TRACKS		INDUCED TRACKS		NEUTRON DOSE (x 10^{14} $n.cm^{-2}$)	FISSION TRACK AGE (m.y.)
			Tracks counted	Density cm^2.	Tracks counted	Density cm^2		
11937	Ben Lomond Obsidian	30	44	40	2628	47306	22.6	0.12 ± 0.02
11912	Kaingaroa Ignimbrite	18	64	46	3786	23654	12.2	0.145 ± 0.02
10793	Murupara Gorge Ignimbrite	16	38	46	6845	42735	23.3	0.155 ± 0.03
11938	Mt. Curl Tephra	7	133	128	1894	32422	9.36	0.23 ± 0.03
11913	Matahina Ignimbrite	18	49	61	1758	17519	12.2	0.26 ± 0.04
P29834	Te Whaiti Ignimbrite	15	75	93	7206	44945	23.3	0.30 ± 0.04
11915	?Rocky Hill Ignimbrite	14	40	100	5507	45792	23.3	0.31 ± 0.06
11916	Rocky Hill Ignimbrite	16	54	105	5435	45187	23.3	0.33 ± 0.06
P20116	Whakamaru Ignimbrite	7	90	180	2474	30745	9.36	0.33 ± 0.05
11914	Te Kopia Ignimbrite	18 8	97 68	193 170	2450 2273	24882 22522	12.2 12.2	0.58 ± 0.08 0.57 ± 0.09
10780	Marshall Ignimbrite	16	72	133	3631	30125	23.3	0.63 ± 0.09
11919	Upper Ahuroa Ignimbrite	14	33	110	2454	24430	23.3	0.64 ± 0.11
11921	?Lower Ahuroa Ignimbrite	16	102	157	2902	18093	12.2	0.65 ± 0.09
10783	Ongatiti Ignimbrite	16	177	295	6803	56397	23.3	0.75 ± 0.08
P25709	Waitearikí Ignimbrite	16	130	296	4061	50467	23.3	0.84 ± 0.11
	Deep-sea core RC9-113, ash layer A (Ninkovich 1968)	6	57	190	756	12410	9.36	0.88 ± 0.16
11929	Aongatete Ignimbrite	16	64	100	2345	16650	23.3	0.86 ± 0.14
11930	Aongatete Volcanics, lower tuffs and breccias	17	122	235	3604	35805	23.3	0.94 ± 0.13
	Deep-sea core RC12-215, oldest ash, 970-72 cm.	8	51	213	847	13962	12.2	1.15 ± 0.23
P29262	"Tridymite Rhyolite"	16	89	223	2153	21307	23.3	1.50 ± 0.23
P29251	Owharoaite (Wilsonite)	20	148	617	2505	30696	23.3	2.89 ± 0.38

SAMPLE NO.	1	2	3	4
%				
SiO_2	73.4	62.9	75.18	73.90
Al_2O_3	12.4	15.6	12.16	12.19
Fe_2O_3	1.0	3.15	-	-
FeO	0.85	2.4	-	-
Total Fe as Fe_2O_3	-	-	1.10	1.68
MgO	0.2	1.35	0.13	0.26
CaO	1.05	3.5	0.94	1.08
*Na_2O	3.55	3.55	3.75	3.48
K_2O	4.00	2.3	3.65	3.67
TiO_2	0.03	0.65	0.11	0.15
P_2O_5	0.02	0.16	0.02	0.04
MnO	0.07	0.12	0.06	0.07
H_2O^+	2.66	3.00	-	-
H_2O^-	0.34	0.52	-	-
**L.O.I.	-	-	3.81	4.21
CO_2	0.03	-	-	-
TOTAL	99.60	99.20	100.91	100.73

KEY

1	Buff Pumice (Martin 1963).
2	Black Pumice (Martin 1963).
3	10793 clear glass shards.
4	10793 brown glass shards.

* Na_2O was analysed by atomic absorption spectrophotometry.

** Loss on ignition between 110°- 1,000°C.

\- not determined.

Table 24. - Major element analyses of pumice and glass shards from Murupara Gorge Ignimbrite (=Kaingaroa Ignimbrite).

a) obsidian previously fission-track dated at 0.095± 0.015 m.y. B.P. and K-A dated at 0.11±0.01 m.y. B.P. (both dates Stipp 1968); fission track obtained by the author = 0.12±0.02 m.y. B.P.

b) glass shards fom Mt Curl Tephra K-A dated at 0.25± 0.12 m.y. B.P. (D. Milne pers. comm.); fission-track dated at 0.23±0.03 m.y. B.P.

c) ash layer A from core RC9-113 paleomagnetically dated at 0.86 m.y. B.P. (Ninkovich 1968); fission-track dated at 0.88±0.16 m.y. B.P.: Further evidence supporting paleomagnetic ages for ashes from deep-sea cores are given by Dymond (1969) and MacDougall (1971).

d) an ash from deep-sea core RC12-215 dated by inferred sedimentation rates at 1.13 m.y. B.P. (<u>see</u> p. 176); fission-track dated at 1.15±0.23 m.y. B.P.

In all cases the fission-track date determined was comparable and within the limits of error of samples previously dated. The results of fission-track dating are given in Table 22. In all cases dates obtained are in agreement with paleomagnetic polarity of rocks sampled (Fig 23). The general agreement of ages determined by different methods, also indicates that previous assumptions made about factors which may affect the accuracy of fission-track dates are probably correct.

The data does not, however, support the conclusions of Storzer and Wagner (1969, 1971) that the density of spontaneous tracks in glasses may decrease with time even if the sample was held at 0°C since it formed. Furthermore, laboratory annealing experiments of Lakatos and Miller (1972) showing similar trends are not supported. It therefore seems unlikely that laboratory annealing data, resulting from experiments made over short periods of time, can be extrapolated to geological time.

<u>Uranium Analysis</u> Uranium contents of rhyolite glass shards dated in this study have not been determined because the critical angle of etching and exact, apparent range of an average fission fragment (both approximating to the product Kα - Kleeman and Lovering 1970) in glass studied are not known.

In order to obtain the product $K\alpha$, the uranium content of typical rhyolite glass will first have to be determined by other methods. Using uranium contents for Taupo Volcanic Zone rhyolites given by Ewart and Stipp (1968) a rough approximation gives a value of $K\alpha = 2-3$.

Discussion of Results

Correlation of Ignimbrites with Deep-Sea Core Ashes Ninkovich (1968) described five ashes in deep-sea cores, labelled a-e from oldest to youngest, from east of N.Z. Since this paper was published more cores were collected in the same general area during cruise 12 of Lamont research vessel CONRAD. One core RC12-215 (Lat. $35^{\circ}28'$S, Long. $167^{\circ}53.5'$W) taken close to cores RC9-113 and 114, contained nine ash-layers (0-5, 227-233, 245-252, 280-293, 552-553, 662-666, 747-759, 919-923 and 970-972 cm). The core is 1045 cm long (all data Ninkovich written comm. 12/5/71). Samples of all the ashes from this core and some from cores previously described were sent to the author to attempt to correlate them on-shore.

In core RC12-215 eight ashes are rhyolitic and the uppermost ash is andesitic and is not considered to have been erupted from N.Z. The core has not been analysed paleomagnetically, but using a sedimentation rate to that of nearby core RC9-114 (i.e. 1.23 cm/1000 yr) ages for the eight rhyolitic ashes are obtained. The ages (Fig 27) are in general agreement with those of Ninkovich (1968) and show that there is an additional tephra between ashes D and E and two older than ash layer A.

Ignimbrite correlatives for the five youngest deep-sea ashes based on fission-track dates, ferromagnesian mineralogy and titanomagnetite composition (Tables 22, 23, 25) are given in Fig 27. The finding of Ongatiti and Whakamaru Ignimbrites ashes in deep-sea cores is not surprising considering that these two ignimbrites together with the Te Whaiti Ignimbrite (=Rangitaiki Ignimbrite) were probably among the largest erupted from Taupo Volcanic Zone (Martin 1961, Blank 1965).

The oldest three ashes in deep-sea cores cannot be

*SAMPLE NO.	CORE NO. + ASH-LAYER	DEPTH FROM TOP OF CORE (cms)	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu	**DOMINANT FERROMAGNESIAN ASSEMBLAGE
	DEEP-SEA CORE ASHES												
	V16-125 E	373-386	-	-	-	-	-	-	-	-	-	-	2
	V18-231 E	208-214	6.69	0.61	0.59	0.57	919	124	52	53	229	57	1 - trace hblde.
	RC12-215 E	227-233	-	-	-	-	-	-	-	-	-	-	1 - " "
	RC9-113 E	142-153	5.82	0.61	0.58	0.61	1079	139	48	50	140	-	2
	RC12-215	245-252	-	-	-	-	-	-	-	-	-	-	1 " "
	RC9-113 D	175-185	5.24	0.71	0.76	0.54	2640	165	73	95	333	-	***3
	RC12-215 D	280-295	5.36	0.73	0.84	0.42	2387	174	95	121	181	-	3
	RC9-114 C	831-832	-	-	-	-	-	-	-	-	-	-	2 - rare biot.
	RC12-215 C	552-553	-	-	-	-	-	-	-	-	-	-	2 - " "
	RC9-113 B	404-405	-	-	-	-	-	-	-	-	-	-	2 - " "
	RC12-215 B	662-666	6.16	0.70	0.75	0.55	2104	184	106	131	352	-	2
	RC9-113 A	471-479	5.13	0.87	0.57	0.55	2003	167	63	82	444	-	3
	RC12-215 A	747-759	6.11	0.77	0.71	0.42	2389	216	88	192	267	-	3
	RC12-215	919-923	-	-	-	-	-	-	-	-	-	-	1
	RC12-215	970-972	5.57	0.78	0.52	0.51	2178	183	178	270	185	-	1 - trace hblde.
	LOCATION	GRID REFERENCE	MT. CURL TEPHRA										
11938	Mt. Curl Road.	N138/953820	5.20	0.55	0.50	0.46	3036	186	86	114	187	41	1 - traces of augite, biot. + hblde.
	" " " (basal 15 cm)	N138/956820	5.37	0.57	0.51	0.40	3136	202	87	126	96	50	

*Sample is housed in the petrological collection of the Geology Department, Victoria University.

**1 = Hypersthene, 2 = Hypersthene + Calcic Hornblende, 3 = Biotite + Calcic Hornblende + Hypersthene.

*** No sanidine was found in the biotite-bearing ashes.

- not determined.

Table 25. - Dominant ferromagnesian mineralogy and titanomagnetite analyses of deep-sea core ashes and Mt. Curl Tephra. Deep-sea core ashes were taken off the east coast of N.Z. by research ships of Lamont-Doherty Geological Observatory and sent to the author by D. Ninkovich of of that institution. Information on titanomagnetite analyses as for Table 6.

definitely correlated with any central North Island ignimbrites. Mineralogically and paleomagnetically the oldest two ashes could be correlated with Rangitoto Ignimbrites (Figs 23, 27, Table 25). No suitable glass has yet been found for dating Rangitoto Ignimbrites, but it would be worthwhile attempting fission-track dating of zircon found in some of these ignimbrites (Blank 1965). The 0.86 biotite-rich ash in deep-sea cores cannot be correlated with any known ignimbrites erupted from Taupo Volcanic Zone or Coromandel area. As ignimbrite volcanism in Taupo Volcanic Zone has been accompanied by subsidence of the Mesozoic greywacke basement to a depth of at least 4 km (Modriniak and Studt, 1959) it is probable that the ignimbrite correlative of this ash is deeply buried by later eruptives. Further drilling through older ignimbrites of Taupo Volcanic Zone may reveal these buried eruptives.

Based on ages implied for stranded shorelines in the south Auckland and Waikato areas Ward (1972) correlated Pleistocene Ashes in Waikato Basin with the deep-sea ashes of Ninkovich (1968). These correlations are also included in Fig 27.

The evidence from deep-sea core tephrostratigraphy indicates that, assuming prevailing wind directions have not changed, explosive rhyolitic volcanism in Taupo Volcanic Zone began about 1.13 m.y. B.P. The pumices assigned an early Pleistocene age by Kear (1957) are then either related to deeply buried, less explosive, rhyolites in Taupo Volcanic Zone or are, more likely, related to rhyolitic volcanism in Coromandel area (Fig 23).

The fission-track dates also show that sources of rhyolitic volcanism have generally trended from west to east with time. This is consistent with the directions of migration of eruptive centres with time in the Mokai Ring Structure and northern, Lake Taupo Volcanic Centre found by Ewart (1968 p. 539) which he believed indicated that the regional tectonic forces were moving in this direction.

Paleomagnetic Data and Fission-Track Dating Cox (1971) concluded from his paleomagnetic study of central North Island volcanic rocks that there were two groups of ignimbrites each

PALEOMAGNETICALLY DATED ASHES FROM DEEP-SEA CORES (Ninkovich 1968)		DEEP-SEA CORE RC12-215 (ages from inferred sedimentation rate of 1.23 cm/1000 yr)	INFERRED CORRELATIVES IN WAIKATO BASIN (Ward 1972)	INFERRED IGNIMBRITE CORRELATIVE IN CENTRAL NORTH ISLAND, N.Z.
Ash-Layer	Age (m.y. B.P.)	Age (m.y. B.P.)		
E	0.27	0.27		Matahina
		0.29		Rangitaiki (= Te Whaiti)
D	0.31	0.32		Whakamaru
C	0.67	0.64	Hamilton ash	?Lower Ahuroa
B	0.73	0.77	Waiterimu ash	Ongatiti
A	0.86	0.87	?early-Kauroa ash	Not known (maybe deeply buried).
		1.07		?Rangitoto
		1.13		

Fig. 27. - Correlation of deep-sea core ashes with ignimbrites in Taupo Volcanic Zone and ashes in the Waikato Basin. Errors on paleomagnetic dates due to uncertainties in K-A ages on which the paleomagnetic time-scale is based are approximately ± 5% of the age.

with directions of magnetisation not significantly different. He concluded that the ignimbrites within each group (Rangitaiki, Te Whaiti, Whakamaru, Manunui and Waiotapu Ignimbrites in one group and Matahina, and Kaingaroa Ignimbrites in the other) were erupted within a period of time not exceeding several centuries.

With the exception of Waiotapu Ignimbrite, the similar titanomagnetite chemistry of ignimbrites within each group supports the conclusions of Cox and suggests that they may be co-magmatic (p. 157). Waiotapu Ignimbrite (Fig 23) has different titanomagnetite composition and was erupted from a more northerly source than other ignimbrites in its paleomagnetic group (Martin 1961). This does not, however, preclude it from being closely related in time to the ignimbrites of its group.

Although the errors on dates of Whakamaru Ignimbrite (= Manunui Ignimbrite and Te Whaiti Ignimbrite) (= Rangitaiki Ignimbrite) overlap (Table 22) the 30,000 yr time between these eruptions is supported by deep-sea core tephrostratigraphy. Core RC12-215 shows that there is at least 28 cm of deep-sea sediment, representing some 35,000 yr between the eruptions of Whakamaru and Te Whaiti Ignimbrites. The time between eruptions of Kaingaroa and Matahina Ignimbrites was some 110,000 yrs.

Fission-track dating of ignimbrites therefore does not support the conclusions of Cox (1971).

The Spontaneous Fission Decay Constant The paleomagnetic data provide a check on the decay constant for spontaneous fission of natural uranium. The value of the decay constant affects the accuracy of fission-track ages and also their comparability with ages derived by other methods. There are two decay constants which are commonly used by different workers. Fleischer and Price (1964b) and Kleeman and Lovering (1971) derived a constant of $6.85 \pm 0.2 \ . \ 10^{-17} yr^{-1}$ and ages using this constant, (which has been used in this study) show concordance with dates derived by other methods. On the other hand, Gentner *et al* (1969) and Durrani *et al* (1971) used a constant of $8.42 \pm 0.1 \ . \ 10^{-17} yr^{-1}$ and this gives dates about 19% younger than those using the former decay constant.

If the constant 8.42 . $10^{-17} yr^{-1}$ was used for determining ages on Waiteariki and Ongatiti Ignimbrites then the dates obtained would be younger than 0.69 m.y. B.P., which would be inconsistent with the reversed polarity of these ignimbrites.

The Relationship between Ahuroa, Marshall, Ranginui and Rocky Hill Ignimbrites The upper Ahuroa, Marshall and Ranginui Ignimbrites all have a distinctive, closely related titanomagnetite composition (Appendix V and Table 23) and similar mineralogy (Martin 1961). Furthermore, Ahuroa and Marshall Ignimbrites are lithologically similar in part (Blank 1965, p. 598) and have close fission-track ages (Table 22). These data thus suggest that the three ignimbrites are either correlatives or at least co-magmatic and erupted within a short time. The following stratigraphic evidence also supports this conclusion.

The lower Ahuroa Ignimbrite was considered by Blank (1965) to be separated by a probable unconformity from upper Ahuroa Ignimbrites. At Gardiners Rd (near Ahuroa Rd) a pumice lenticulite (No. 485) overlying Ongatiti Ignimbrite and underlying upper Ahuroa Ignimbrite (No. 478) is provisionally correlated with "pumice-breccia" (Nos. 486, 487) recently exposed in road cutting near Waipapa Damsite (Fig 1). The two tentative correlatives have similar titanomagnetite chemistry and mineralogy but differ from that of the overlying units and therefore support the evidence of an unconformity within the Ahuroa Ignimbrites (Blank 1965).

The "pumice breccia" near Waipapa is dated at 0.65±0.09 m.y. B.P. (Table 22) and is therefore slightly older than the Marshall and Upper Ahuroa Ignimbrites. It grades upwards into ash which carries a well-developed paleosol which in turn is overlain by more ash (No. 484) which is capped by Ranginui Ignimbrite (No. 509). It is not certain if this ignimbrite is in situ.

If the Ranginui Ignimbrite, near Waipapa is in place as seems probable from the/similar titanomagnetite composition of underlying ash (No. 484), then the chemical evidence indicates that it is closely associated in time with eruption of Upper Ahuroa and Marshall Ignimbrites. Determination of the polarity of Ranginui Ignimbrite could confirm the validity of this conclusion.

The distinctive titanomagnetite composition of the three ignimbrites with high Ti and Mn and low V contents maybe either due to the failure of ilmenite to crystallise or to the initial composition of the magma.

Fission-track dating shows that the Marshall Ignimbrite is not a correlative of Rocky Hill Ignimbrite, as suggested by Martin (1961 p. 461), the latter being some c. 300,000 yrs younger. The age and titanomagnetite composition of Rocky Hill Ignimbrite is similar to that for an ignimbrite of normal polarity dated at 0.31±0.06 m.y. B.P. near Maraeora (No. 472) which was previously mapped as Ongatiti Ignimbrite by Blank (1965). The error on the dates for Rocky Hill, Te Whaiti and Whakamaru Ignimbrites overlap, so it is still unclear whether the Whakamaru Ignimbrite is younger than the Rocky Hill Ignimbrite as tentatively proposed by Blank (1965). The similar titanomagnetite composition and similar age of Rocky Hill, and Whakamaru and Te Whaiti Ignimbrites suggests they may be comagmatic. These ignimbrites were probably part of an eruptive sequence which produced voluminous and explosive rhyolitic volcanism between c. 0.29-0.33 m.y. B.P. Following these outpourings, large scale collapse, particularly on the eastern side, took place within the Taupo Volcanic Zone.

<u>Age of the "Castlecliffian-Hawera Boundary", Bay of Plenty</u>

The widespread Matahina Ignimbrite erupted from Okataina Volcanic Centre (Bailey 1965) overlies Castlecliffian and Early Haweran (middle-upper Pleistocene) marine and estuarine beds at Matata on the Bay of Plenty Coast (Healy and Ewart 1965). This ignimbrite also overlies Lukes Farm Formation beds (freshwater) which partly correlate with coastal beds and the widespread and stratigraphically important Huka Falls Formation (Grindley 1965). Pollen assemblages from Huka Falls and Lukes Farm beds (Harris <u>in</u> Grindley 1965) show that the Castlecliffian -Haweran boundary, representing an interglacial-glacial boundary, occurs within these beds. The beds spanning the boundary are enclosed by the Matahina and Rangitaiki (= Te Whaiti)

Ignimbrites (Grindley 1965) and fission-track dates for these ignimbrites shows this age to lie between 0.26-0.30 m.y. B.P.

Mt Curl Tephra The name Mt Curl Tephra is given to tephra that mantles the oldest late Quaternary landscapes in the SW part of the North Island. The tephra immediately pre-dates the cutting of a marine bench thought to have been cut during the penultimate interglacial high sea-level and it almost immediately post-dates a major aggradation terrace considered to have been formed during the ante-penultimate glaciation (D. Milne pers. comm.)

The fission-track date on this tephra of 0.23±0.03 m.y. B.P., therefore, is close to a glacial-interglacial boundary. Mt Curl Tephra is rhyolitic in composition and contains a dominantly hypersthene ferromagnesian assemblage with lesser amounts of calcic-hornblende. The titanomagnetite composition (Table 25) and age of the tephra indicates that it was not associated with an ignimbrite eruption.

Concluding Remarks

The tempo of rhyolitic volcanism in Taupo Volcanic Zone has been previously discussed (Healy 1971). The data presented here indicates that there has not been any periodic timing of ignimbrite eruptions, although it does reveal that many were closely spaced in time. No fresh glass for dating was found in any samples of Mamaku, Rangitaiki, Waiotapu, Paeroa, Te Weta, Ranginui and Rangitoto Ignimbrites examined. More detailed examination of these ignimbrites, as well as other pyroclastic rocks and lavas will undoubtedly yield fresh glass and zircon for fission-track dating. Such studies will allow detailed timing and history of events in volcanic centres to be determined; a necessary step in undertaking any volcanic risk studies.

Finally, the fission-track method will allow dating of glass shards from tephras in such areas as Wanganui Basin and Hawkes Bay where they form important stratigraphic markers (Fleming 1953, and Kingma 1972). This dating would allow the formation of an absolute time-scale for dating N.Z. stages and important geological events. Such studies are currently proceeding.

GENERAL CONCLUSIONS

1. Laboratory studies show that titanomagnetite chemistry, and ferromagnesian mineralogical assemblage, together serve to identify most ignimbrites erupted from Taupo Volcanic Zone, New Zealand.

2. There are no systematic vertical changes in titanomagnetite composition in ignimbrites studied, although in parts of the Mamaku and Rocky Hill Ignimbrites titanomagnetite chemistry has been altered, probably due to vapour phase activity.

3. Titanomagnetites from weathered pyroclastic rocks do not show any chemical differences from those sampled from fresh rocks of the same formation.

4. A method developed for fission-track dating rhyolitic glass provides ages using decay constant $\lambda_f = 6.85 \times 10^{-17} yr^{-1}$ which are consistent with those derived from identical samples previously dated. The agreement of dates show that results of short term laboratory annealing experiments can not be extrapolated to geological time.

5. Eight rhyolitic ashes are recognised in deep-sea cores taken east of New Zealand. The five youngest can be correlated with central North Island ignimbrites. The two oldest (1.07 and 1.13 m.y. B.P.) may correlate with ignimbrites of the Rangitoto Ignimbrites, while the correlative of the third oldest (0.86 m.y. B.P.) is probably deeply buried in Taupo Volcanic Zone.

6. Explosive rhyolitic volcanism in Taupo Volcanic Zone probably commenced from the western side c. 1.13 m.y. B.P. Since this time sources of acid volcanism have generally trended to the east with time.

7. Large scale collapse in the eastern Taupo Volcanic Zone occurred c. 0.29-0.33 m.y. B.P. following voluminous eruptions of ignimbrites.

8. Ignimbrite eruptions from Taupo Volcanic Zone have been irregularly spaced, but some were closely spaced in time. The

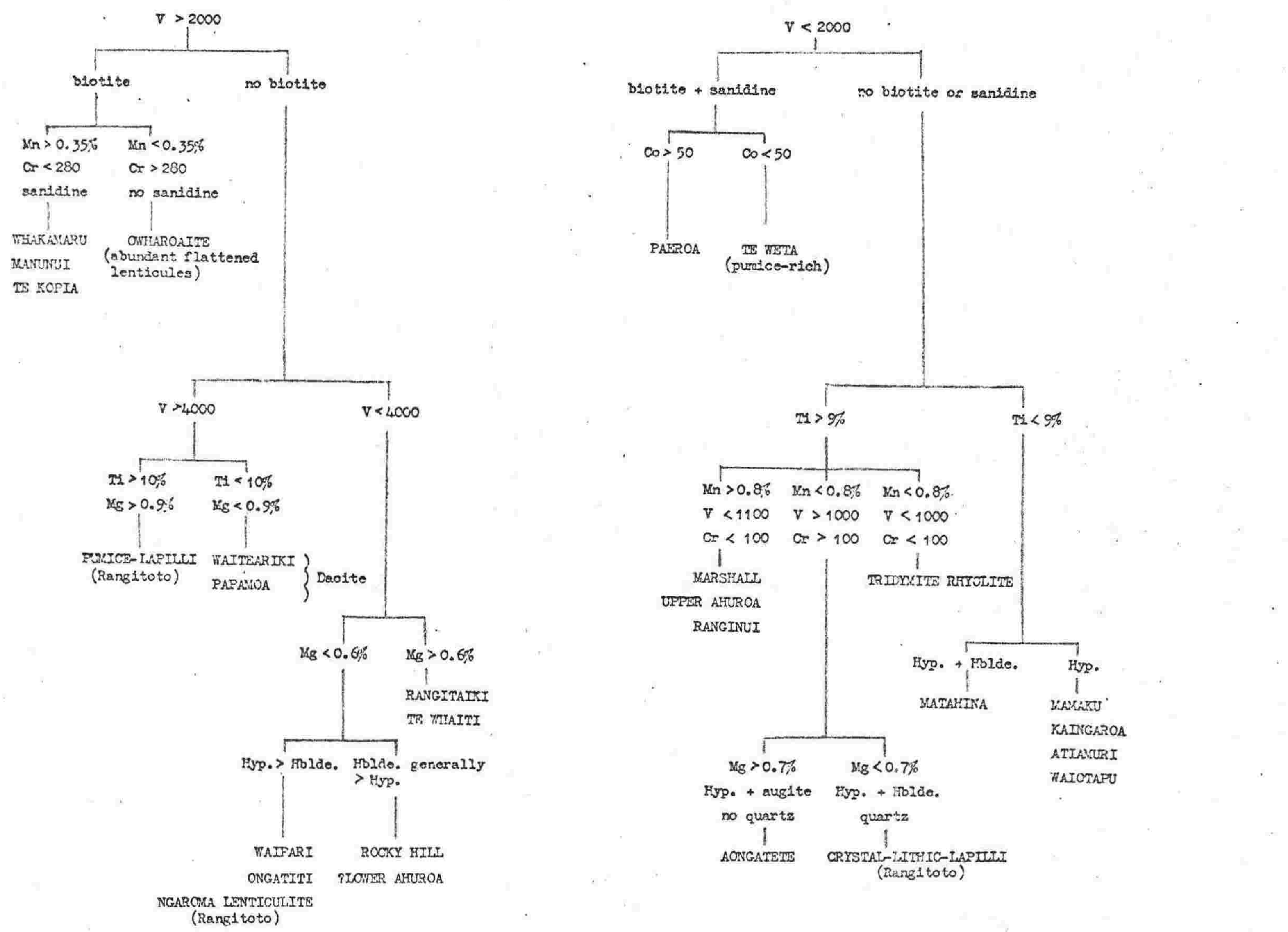

Fig. 24. - Generalised identification scheme for acidic ignimbrites erupted from Taupo Volcanic Zone (all 44,000 yr B.P.) using dominant ferromagnesian mineralogy elemental abundances in titanomagnetite (all values in ppm unless otherwise indicated) and to a lesser extent bulk chemistry.

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APPENDIX I

METHODS OF ANALYSIS

The following instruments were used in the analysis of separate rocks and minerals; x-ray fluorescence spectrometer, atomic absorption spectrophotometer, electron-microprobe analyser and optical emission spectrograph.

X-ray fluorescence (X.R.F): Whole rock samples were dried for 24 hrs at 110°C. Samples were prepared as glass fusion discs following the procedure of Norrish and Hutton (1969). Rocks were analysed in duplicate.

The concentrations of each major element were determined relative to an artificial standard FSL - 7. Major element concentrations for international rock standards (G - 2, AGV - 1 and GSP - 1 - Flanagan 1969) were also determined by the same method as a check. Corrections for background, drift and matrix corrections were made after the method of Norrish and Hutton (1969).

The operating conditions of the Siemens X.R.F. (SRSI) used are given in Table 26.

Atomic absorption spectrophotometic analyses (A.A.): Analyses of whole rocks for Si, Al, Mg, Na, Ca, Fe and Mn were made on a Varian Techtron model AA-4.

Rock samples, as with samples analyses by X.R.F., were first ground in a tungsten carbide tema-mill for upto 45 seconds. The ground samples were then fused in a platinum crucible with a mixture of $Li_2B_4O_7$, Li_2CO_3 and La_2O_3 (in the ratio of 6 : 1 : 1.45), dissolved in 4% HCl and then made upto 250 ml. using deionised water.

Solutions were run on the A.A. and curves of absorbance plotted against concentration were constructed using international rock standards (JB- 1, SY - 3, DRN, T - 1, GSP - 1, BCR - 1, GSP - 1, AGV - 1, G - 1, G - 2, DTS, PCC - 1, Mica - Fe Biotite and blanks for background corrections) which were prepared in the same way as the rock samples.

ELEMENT	CRYSTAL	TUBE	kV	mA	COUNTING TIME (secs.)
Ti	LiF 200	Cr	35	16	20
Fe	LiF 200	Cr	45	30	20
Ca	LiF 200	Cr	35	14	20
Mn	LiF 200	Au	40	20	20
Si	PET	Cr	60	40	20
Al	PET	Cr	60	40	20
K	PET	Cr	45	30	20
P	PET	Cr	60	40	20
Mg	ADP	Cr	60	40	80

All radiations using vacuum with coarse collimator (0.4°) and gas flow proportional counter (P 10 gas, 90% argon + 10% methane).

Table 26. - Operating conditions for X-ray fluorescence spectrograph.

Electron microprobe analysis: Electron microprobe work was carried out at the N.Z. Geological Survey using an AEI model SEM2 - under the supervision of Dr. G.A. Challis.

For Fe-Ti oxides analysed the following standards were used.

Ilmenite K13-131.8 and Magnetite L4-175 (Anderson 1968, p. 708) and chromite MB-5(Irvine 1967, p. 94).

Analyses were made on carbon coated polished grain mounts under the following conditions.

Accelerating voltage	20 Kv
Beam Current	0.2 mA
Spot size	0.25-0.5 microns.
Counting time	10-20 seconds

Six elements were analysed simultaneously with upto five spot determinations being made for each element.

All counts were corrected for background and dead time (3 microsecs.) when counts exceeded 4000/sec.

Calculation of Fe_2O_3 was made after the method of Carmichael (1967 p. 39).

Optical emission spectroscopy: Details of the spectrographic apparatus used, operating conditions and element lines used are given in Kohn (1970). Detection limits for lines read are: 5 ppm for V, Co and Ni, 10 ppm for Mn, Cr, Zr, and Cu, and approx. 500 ppm for Ti, Mg and Ca. Further details on the preparation of standards and general procedure used are given by Tennant (1966).

APPENDIX II

Analyses of titanomagnetites from post c. 44,000 yr B.P. central North Island tephras. Information on analyses as for Table 6 (Part 1).

*Numbers prefixed by "P" refer to samples in the N.Z. Geological Survey petrological collection. Numbers with no prefix refer to samples which belong to the petrological collection of the Geology Department, Victoria University.

Letters preceding details of sample location refer to collectors other than the writer.

a - W.A. Pullar, b - J.E. Cox, c - H.W. Wellman,
d - R.G. Law, e - V.E. Neall, f - W.W. Topping,
g - K.B. Lewis, h - J.W. Cole, i - A.R. Duncan,
j - C.G. Vucetich, k - J.D.G. Milne m - I.A. Nairn,
p - L. Singh.

All grid references are based on the national thousand-yard grid of the 1:63,360 topographic map series (NZMS 1). Date of publication of maps used in this study are:

1953 - N30, N106, N133,
1956 - N92,
1962 - N78, N141, N145, N146,
1964 - N7, N76, N84, N102, N134,
1965 - N53, N57, N58, N67, N77, N98,
1966 - N122,
1967 - N49, N68, N75, N85, N96, N105, N114, N115,
1968 - N24, N86, N93, N112, N121,
1969 - N69, N94, N103, N116, N142, N149, N169 (interim series),
1970 - N95,
1971 - N83.

Sample Nos. (Table 4) not given in following Tables are:

11931 = Analysis No. 148, and 11932 = Analysis No. 149.

11867 = Waiohau Ash, Mt. Tarawera, gully SE Wahanga Dome, N77/985942.

11884 = ash size material of sample 11883 which comprises only pumice lapilli.

11888 = Mangaone member (d), pumice in paleosol, River Rd, Onepu, Rangitaiki Plains, N77/190183.

11890 = Mangaone member (c), tephra-flow containing charred logs, locality as for 11888.

11891 = Mangaone member (c), paleosol, coarse ash, locality as for 11888.

11898 = Mangaone member (b_2), ash size material of sample 11897 (which is dominantly lapilli and block size).

11889 = Mangaone member (e), pumice lapilli and blocks, basal 20 cm, locality as for 11888.

Abbreviations:

(T.L.) = type locality.

(A) = ash-size tephra, (L) = lapilli-size tephra,

(B) = block-size tephra.

(15 cm T) = total thickness of tephra at a section = 15 cm.

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
		TARAWERA FORMATION											
1		Rotomahana Mud, cutting on crest of Tikitere Hill, Rotorua-Whakatane Highway, (A).	N76/829134	4.70	0.95	0.63	1.22	1518	141	35	39	328	40
2		Tarawera Lapilli, near Waiohau, (L).	N77/284934	5.42	1.05	0.60	0.91	1251	72	27	73	289	47
		LOISELS PUMICE											
3	*11840	[a]Ohiwa Harbour, Bay of Plenty, (B).	N69/570212	4.72	1.75	0.78	0.75	2492	104	153	76	31	140
4		[b]Ocean Beach, Whangarei Heads, (B).	N24/073852	4.78	1.63	0.78	1.33	1181	31	101	55	34	113
5		Tatapouri Beach, Gisborne District, (B).	N98/519389	5.22	1.17	0.51	0.76	1033	10	125	148	21	110
6		[c]Waimarama Beach, Hawkes Bay District, (B).	N142/442985	5.79	1.28	0.48	1.15	1175	141	78	54	58	90
7		[d]Harataonga Bay, Great Barrier Island, (B).	N30/990434	7.16	0.91	0.57	0.68	1519	74	80	66	65	49
8		Whiritoa Beach, south end, Coromandel Peninsula, (B).	N53/393079	7.31	1.19	0.52	0.65	2509	131	105	54	53	55
9		[c]Whatuwhiwhi Beach, Northland, (B).	N7/912975	7.44	1.01	0.59	0.96	1135	11	72	46	44	53
		KAHAROA ASH											
10		Mt. Tarawera gully SE Wahanga Dome, basal 30 cm (approx. 20 m T), (A,L).	N77/985942	5.43	0.71	0.77	0.26	1167	65	36	69	149	60
11		as above, 5 - 5.5 m above base, (L).	" "	5.08	0.72	0.80	0.51	1266	73	33	40	595	61
12		as above, 8.3 - 8.9 m above base, (L).	" "	4.98	0.48	0.77	0.64	1199	54	35	43	932	62
13		as above, 11.3 - 11.7 m above base, (L).	" "	4.98	0.66	0.78	0.81	1223	29	33	21	925	63
14		as above, 16.8 - 17.1 m above base, (L).	" "	5.53	0.46	0.83	0.64	1383	71	24	52	1081	64

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
15		Northern Boundary Rd : basal 6 cm (152 cm T), (A).	N86/032806	6.61	0.43	1.07	0.24	1071	60	49	54	804	51
16		as above, 43 - 51 cm above base (L).	" "	5.68	0.70	0.87	0.51	1023	50	45	40	993	77
17		as above, 76 - 90 cm above base, (A,L).	" "	6.31	0.43	1.19	0.34	974	46	43	38	1027	35
18		as above, 122 - 132 cm above base, (A).	" "	6.11	0.69	1.11	0.54	1420	110	48	43	899	35
19		as above, 122 - 132 cm above base, (B).	" "	5.50	0.77	0.98	0.83	1432	67	56	45	420	50
20	11841	as above, 138 - 144 cm above base, (A).	" "	6.05	0.37	0.98	0.21	1638	58	47	43	1096	50
21		as above, 147 - 150 cm above base in paleosol, (A).	" "	6.38	0.33	0.89	0.11	1661	58	46	43	365	44
22		Murupara, cutting on terrace, Rotorua-Waikaremoana Highway, (L).	N86/165627	6.75	0.37	1.27	0.49	986	68	37	23	1601	29
23		Mangawiri Stream, cutting on south side bridge, Rotorua-Waikaremoana Highway, (L).	N95/177580	5.73	0.31	0.97	0.41	882	21	49	21	1487	49
24		Galatea : cutting in terrace, Te Teko-Murupara Rd, basal 10 cm, (82 cm T), (A,L).	N86/206783	5.53	0.65	0.71	0.45	1016	40	32	26	621	41
25		Matahina Rd, basal 50 cm, (168 cm T), (A,L).	N86/060860	5.81	0.61	0.66	0.55	834	20	23	19	1046	58
26		Matahina Rd, 143 - 158 cm above base, (A).	N86/060860	5.49	0.42	0.71	0.65	1391	31	29	31	1029	57
27	11842	Ruatahuna - left bank of Ruatahuna Stream near bridge, Rotorua-Waikaremoana Highway, (L).	N96/370443	5.85	0.43	0.66	0.23	850	19	23	19	1017	52
28		Lake Rotoehu, road cutting, Rotorua -Whakatane Highway, basal 10 cm (L).	N77/976164	5.27	0.57	0.72	0.80	1263	25	30	23	1276	53
29		Cutting on crest of Tikitere Hill, Rotorua-Whakatane Highway, basal 8 cm (38 cm T), (L).	N76/829134	5.64	0.54	0.78	0.43	1482	71	31	27	830	48
30		as above, 29 - 37 cm above base, (A)."	"	5.26	0.51	0.75	0.16	1417	66	32	25	596	49

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
31		L. Rotoiti : Waiiti Maori School, Rotorua-Whakatane Highway, 18 - 38 cm above base, (104 cm T), (L).	N77/944149	5.58	0.62	0.72	0.45	1368	49	46	23	477	54
32		as above, 51 - 64 cm above base, (A,L).	" "	5.21	0.59	0.68	0.73	1350	35	26	27	1147	55
33		as above, 71 - 84 cm from base, (A,L).	" "	5.58	0.49	0.75	0.35	1476	59	42	26	857	56
34		Mt. Tarawera, track up mountain, Flow Breccia member, (A,L).	N77/981906	5.20	0.65	0.70	0.63	1457	35	36	44	781	44
35		Awakeri; Rotorua-Whakatane Highway, (swamp), (A).	N68/325208	6.38	0.49	0.76	0.21	1580	78	36	31	24	50
36		Iwitea Pa, small hill at rear of pa, (A).	N116/898938	6.28	0.51	0.66	0.29	816	35	30	35	92	51
37		Tiniroto, R.J. Berry's farm (swamp), (A).	N106/935255	8.06	0.71	0.71	0.30	1059	98	45	31	240	-
		TAUPO PUMICE FORMATION											
38	*P28874	Upper Taupo Pumice, road leading up to Hinemaiaia Plateau, (A,L).	N103/not given	8.42	0.77	0.81	0.30	1903	141	60	72	104	64
39	P28875	Lower part Upper Taupo Pumice, road leading up to Hinemaiaia Plateau, (L).	N103/not given	7.52	0.88	0.84	1.16	690	127	49	41	106	58
40		^e^Cutting near Waikato Falls, Upper Taupo Pumice, (B).	N112/309830	7.87	0.75	0.66	0.74	1043	143	50	58	82	65
41		^e^Old Ketetahi Track, (B).	N112/133894	7.63	0.89	0.92	0.77	968	162	50	55	78	68
42		Mapara Rd, rhyolite block member (B).	N94/466364	7.18	0.77	0.66	0.24	974	147	39	39	74	105
43		^p^Raised beach - north Awhea River mouth, (B).	N169/023958	7.64	0.83	0.83	0.78	590	119	35	50	65	63
44		Top of Pukeonake Cone (B).	N112/066824	7.41	0.82	0.59	0.51	896	220	51	85	60	100
45		Taupo-Napier Highway, 3.6 km SE from Rangitaiki River, Upper Taupo Pumice, (L).	N103/861127	6.65	1.20	0.66	0.79	572	100	15	20	68	42
46		Kaingaroa Headquarters : cutting on north side of road leading east, basal 20 cm (91 cm T), (A,L).	N86/023711	8.16	1.06	0.69	0.57	596	122	16	25	62	35

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
47	11843	Napier-Taupo Highway, opposite De Bretts Hotel, Taupo Lapilli, basal 30 cm (152 cm T), (B).	N94/564354	7.92	1.06	0.69	0.54	649	131	16	27	68	22
48		Tiniroto, R.J. Berry's Farm (swamp) (A).	N106/935255	9.01	0.88	0.68	0.40	643	137	18	26	70	24
49		Wairakei-Putaruru Highway, basal 10 cm (L).	N94/516544	7.92	0.69	0.80	0.66	847	117	35	55	83	43
50		Awakeri, (swamp), Rotorua-Whakatane Highway, (A).	N68/325208	6.56	-	0.95	-	960	161	51	60	21	-
51	11844	Opoutere Beach, north end, (Ohui), Coromandel Peninsula, (L).	N49/377331	8.17	0.75	0.84	0.67	780	132	30	37	61	47
52	P28841	Rotongaio Ash, Taupo Pumice Pit.	N94/589347	7.85	0.76	1.07	0.16	1252	154	49	54	154	59
53		Rotongaio Ash, cutting on left, 300 m S of Palmer Rd turnoff, Taupo-Rotorua Highway, (A).	N94/598486	7.62	0.83	0.90	0.34	797	136	35	40	166	49
54		Rotongaio Ash, Napier-Taupo Highway (27 cm T), (A).	N94/572354	7.93	0.82	0.77	0.44	749	121	22	49	162	42
55	P28842	Putty Ash - Tsg 5 Taupo Pumice Pit, (A).	N94/589347	7.39	0.66	0.75	0.49	989	99	39	57	79	48
56		Putty Ash, Napier-Taupo Highway (A).	N94/572354	7.18	0.72	0.66	0.64	1211	100	48	60	113	53
57		Hatepe Lapilli-Murupara, cutting on terrace, Rotorua-Waikaremoana Highway, (L).	N86/165627	7.88	0.77	0.55	0.69	865	124	28	33	88	39
58		Hatepe Lapilli, Kaingaroa Headquarters, cutting on north side of road leading east, (L).	N86/023711	7.06	0.87	0.75	0.61	959	104	38	48	66	49
59		[a]Hatepe Lapilli - waterborne, Whakatane Borough, 183 - 244 cm from surface, (A,L).	N69/426255	8.66	0.71	0.61	0.44	819	127	39	36	82	86
60		Hatepe Lapilli, Tiniroto, R.J. Berry's Farm (swamp), (A,L).	N106/935255	8.66	0.87	0.77	0.40	895	115	38	47	77	58
61		Hatepe Lapilli, Napier-Taupo Highway, (L).	N94/572354	8.09	1.05	0.59	0.50	1398	137	36	55	105	20
62	P28843	Hatepe Lapilli, Tsg 6, Taupo Pumice Pit, (L).	N94/589347	7.14	0.73	0.78	0.59	836	101	35	53	98	61
63	P28844	Hatepe Lapilli, Tsg 7, Taupo Pumice Pit, (L).	" "	7.53	0.78	0.69	0.55	1667	171	48	78	107	73

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
64	P28845	Hatepe Lapilli, Tsg 8, Taupo Pumice Pit, (L).	" "	8.03	0.79	0.79	0.64	853	106	39	47	91	65
65	P28366	Waitahanui Breccia, Hatepe Hill, (A).	N103/513174	7.31	0.79	0.82	0.58	1095	114	62	97	257	82
66		Waitahanui Breccia, " " , (B).	N103/515174	7.20	0.90	0.58	0.53	622	92	33	72	347	76
67		Waitahanui Breccia " " , (A).	" "	7.19	0.80	0.74	0.67	642	84	13	83	414	92
		MAPARA TEPHRA											
68	11845	Mapara Rd, basal 6 cm (10 cm T), (A,L).	N94/466364	6.73	0.86	0.81	0.44	780	113	35	38	97	50
69		Road to Burrows Quarry - Tauhara basal 15 cm (61 cm T), (A,L).	N94/647394	7.55	0.90	0.87	0.30	633	106	33	41	71	39
70		as above, 30 - 36 cm above base, (A).	N94/647394	7.17	0.80	0.69	0.28	611	97	34	28	95	57
71	P28846	Tsg 10 Taupo Pumice Pit, (L).	N94/589347	8.01	0.71	0.85	0.32	659	98	34	50	92	41
72		Tiniroto, R.J. Berry's Farm, Tsg 9 - 13, (swamp), (A).	N106/935255	-	0.79	0.69	0.48	410	60	30	30	-	-
73		Napier-Taupo Highway, 34 - 40 cm above base, (46 cm T), (A,L).	N94/564354	7.97	0.63	0.69	0.36	705	113	35	44	87	48
74		Jamiesons Farm, Rangitaiki Plains, (swamp), (A).	N69/368239	7.44	0.80	0.83	0.62	570	100	46	38	83	63
75		Rotorua-Taupo Highway, basal 5 cm, (11 cm T), (A,L).	N94/695523	7.27	0.76	0.88	0.66	469	87	31	20	99	49
		WHAKAIPO TEPHRA											
76		Mapara Rd, basal 15 cm (38 cm T), (L).	N94/466364	8.45	0.50	0.70	0.35	443	73	35	24	454	61
77		as above, 15 - 23 cm above base, (L).	" "	7.55	0.54	0.79	0.33	462	82	36	22	503	53
78	11846	Road to Burrows Quarry - Tauhara, basal 15 cm, (20 cm T), (L).	N94/647394	9.57	0.55	0.96	0.24	558	96	39	26	300	51

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
79		Napier-Taupo Highway, Tsg 11, 29 - 34 cm above base, (40 cm T), (A).	N94/564354	7.41	0.67	0.80	0.22	924	106	43	40	246	71
80	P28848	*Taupo Pumice Pit, Tsg 13 (A,L).	N94/589347	9.35	0.57	0.98	0.28	419	74	34	33	489	-
81	P28847	" " " Tsg 12 (A,L).	" "	7.31	0.52	0.80	0.38	453	55	36	36	654	52
82		Jamiesons Farm, Rangitaiki Plains, (swamp), (A).	N69/368239	9.96	0.49	0.85	0.42	539	73	43	50	294	89
		WAIMIHIA LAPILLI FORMATION											
83	11847	Napier-Taupo Highway, basal 20 cm (c. 195 cm T), (B).	N94/572354	7.28	1.23	0.79	0.67	699	149	24	27	332	41
84		as above, Tsg 14a, 180 - 190 cm above base, (A).	" "	7.91	0.86	0.61	0.59	706	127	23	28	285	32
85		Napier-Wairoa Highway, basal 20 cm (51 cm T), (L).	N114/327763	8.42	0.70	0.59	0.43	653	125	20	34	359	52
86		as above, (A). 26 - 40 cm.	" "	7.78	0.66	0.81	0.22	1024	121	47	63	233	66
87		Wairakei-Putaruru Highway, basal 20 cm, (51 cm T), (B).	N94/516544	8.02	0.78	0.89	0.46	1023	135	55	68	380	60
88		Wairakei-Putaruru Highway, 43 - 48 cm above base, (A).	N94/516544	7.80	0.84	0.99	0.36	1094	121	50	60	317	51
89	P28852	Tsg 14d, Taupo Pumice Pit, (A,L).	N94/587347	8.32	0.62	0.75	0.32	863	118	50	88	342	56
90		[a]Tamarau, Poverty Bay, (A,L).	N98/431355	9.76	0.73	0.62	0.50	693	109	36	40	347	63
91		[f]Ohakune Mountain Rd, (10 cm T), (A).	N121/996602	9.17	0.72	0.55	0.06	1008	201	43	75	226	99
92		Desert Rd, (17 cm T), (A,L).	N122/219675	10.44	1.29	0.77	0.25	989	136	50	87	225	126
93		[f]Rangipo Desert , (3 cm T), (A).	N122/165595	7.61	0.62	0.63	0.17	709	128	30	36	222	42
94		Poukawa Swamp (6 cm T), (L).	N141/143055	9.11	0.64	0.83	0.98	753	123	45	58	105	63
95		Tiniroto, R.J. Berry's Farm, (swamp), basal 14 cm (28 cm T), (L).	N106/935255	9.98	0.82	0.67	0.34	719	154	26	39	80	36
96		as above, 25 - 28 cm above base, (A).	" "	9.30	1.22	0.54	0.26	1122	126	34	65	92	45
97		[g]Waimarama Beach, (L).	N142/407973	6.79	0.74	0.59	0.88	632	101	18	74	226	23
98		[g]Kairakau Beach, (L).	N141/338844	8.87	0.77	0.52	0.85	920	145	28	48	109	56

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
		ROTOKAWAU ASH											
99		Cutting on crest of Tikitere Hill, Rotorua-Whakatane Highway (T.I.), 65 - 75 cm from base, (99 cm T), (A).	N76/829134	6.20	0.63	0.61	0.28	2020	201	82	71	301	41
100		Rotorua-Whakatane Highway, (90 cm T), (A).	N76/842139	5.18	0.61	0.73	0.17	2238	109	66	72	174	40
101		Mourea, Rotorua-Tauranga Highway, basal 15 cm, (47 cm T), (A).	N76/796148	5.90	0.61	0.92	0.13	1850	95	58	65	1050	38
102		1.3 km south of Mourea township, Rotorua-Tauranga Highway, basal 8 cm (51 cm T), (A).	N76/798139	6.18	0.63	0.93	0.16	1952	101	62	55	844	44
103	11848	L. Rotoiti : Waiiti Maori School on Rotorua-Whakatane Highway, 18 - 23 cm above base (31 cm T), (A).	N77/944149	6.63	0.75	0.66	0.10	1799	116	62	45	125	60
		WHAKATANE ASH											
104	11849	Murupara - (T.I.) cutting at intersection of two logging roads, basal 20 cm (61 cm T), (A,L).	N86/137654	5.25	0.62	0.69	0.33	1273	49	40	55	625	36
105		Mt. Tarawera, gully SE Wahanga Dome, basal 20 cm, (approx. 300 cm T), (L, B).	N77/988948	5.49	0.57	0.63	0.13	1245	41	32	23	820	37
106		^{h}Mt. Tarawera, track up mountain, basal 25 cm (58 cm T), (L).	N77/981906	5.50	0.49	0.85	0.16	1450	75	57	71	1089	47
107		Gavin Rd, Rerewhakaaitu, basal 10 cm (69 cm T), (L).	N86/993831	4.90	0.48	0.87	0.19	1384	51	52	42	1048	33
108		as above, 25 - 34 cm above base, (L).	" "	5.58	0.49	0.66	0.13	1214	66	45	26	1168	34
109		as above, 53 - 58 cm above base, (A,L).	" "	5.48	0.44	0.78	0.20	1318	122	56	84	1662	52
110	11850	^{h}Gavin Rd, 64 - 68 cm above base, in paleosol, (A).	" "	5.12	0.59	0.69	0.37	1197	44	27	14	1599	38

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
111		Matahina Rd, Rerewhakaaitu, basal 15 cm (166 cm T), (B,L).	N86/060860	5.21	0.55	0.64	0.14	1521	74	44	37	974	26
112		as above, 46 - 54 cm above base, (B,L).	" "	5.00	0.60	0.63	0.23	1325	76	41	34	891	52
113		as above, 118 - 126 cm above base, (L).	" "	4.89	0.45	0.63	0.15	1320	67	46	28	984	23
114		as above, 143 - 151 cm above base, (A,L).	" "	5.08	0.59	0.57	0.14	1233	83	48	42	530	51
115	11851	L. Rotoehu, Rotorua-Whakatane Highway basal 12 cm (145 cm T).	N77/976164	5.22	0.43	0.55	0.11	1190	49	35	16	1128	20
116		as above, 78 - 83 cm above base, (L).	" "	4.94	0.52	0.67	0.10	1345	62	38	17	871	20
117		Democrat Rd ; Rerewhakaaitu, basal 8 cm (43 cm T), (A,L).	N86/934824	4.98	0.66	0.69	0.20	1199	42	29	22	929	40
118		Awakeri : Rotorua-Whakatane Highway, (swamp), (A,L).	N68/325208	6.87	0.92	0.57	0.10	1441	55	32	29	116	39
119		Tiniroto : R.J. Berry's Farm, (swamp), (A).	N106/935255	6.45	0.80	0.62	0.38	1132	61	48	54	95	35
120		Iwatahi Gully, Napier-Taupo Highway, basal 8 cm (15 cm T), (L).	N103/735200	5.57	0.65	0.61	0.20	1251	109	47	40	447	38
121		Collin's Farm, southern side Waitahanui River, basal 6 cm, (13 cm T), (A).	N103/622142	5.25	0.60	0.65	0.09	1267	95	52	52	353	62
			WHANGAMATA ASH										
122	11852	Whangamata-Waihi Highway, road cutting, basal 20 cm (66 cm T), (B).	N49/342132	6.11	1.15	0.92	0.14	2727	298	88	174	252	93
123		as above, 30 - 43 cm from base, (B).	" "	6.45	1.01	0.82	0.15	2388	226	93	113	168	97
124		as above, 46 - 61 cm from base (L,B).	" "	6.06	0.99	0.77	0.11	2524	269	93	106	139	75
125		Whangamata-Waihi Highway, road cutting, basal 20 cm (55 cm T), (B).	N53/370098	6.20	1.17	0.78	0.11	3277	369	108	210	143	93

HINEMAIAIA ASH

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
126	11853	Collin's Farm, Southern side Waitahanui River, basal 6 cm, (30 cm T), (A,L).	N103/622142	6.66	0.70	0.61	0.45	936	101	38	48	313	88
127		as above, 20 - 25 cm above base, (A).	" "	6.78	0.92	0.75	0.11	1050	95	52	52	236	69
128		Mapara Rd, 15 cm from top, (28 cm T), (A).	N94/466364	6.75	0.53	0.64	0.67	747	83	36	40	299	84
129	P28856	Taupo Pumice Pit, Tsg 16c+d.	N94/587347	8.08	0.55	0.82	0.29	887	85	44	55	663	50
130		Iwatahi Gully, basal 10 cm, (22 cm T), (A,L).	N103/735200	7.80	0.69	0.59	0.12	1214	84	57	88	138	84
		National Park-Taupo Road, (A).	N112/125924	6.55	0.59	0.65	0.08	762	99	34	35	176	80

MAMAKU ASH

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
131		Democrat Rd, basal 8 cm (28 cm T), (A).	N86/934824	4.81	0.59	0.93	0.13	1866	85	50	51	1037	38
132	11854	Cutting on crest of Tikitere Hill, Rotorua-Whakatane Highway, basal 20 cm (150 cm T), (A,L).	N76/829134	5.20	0.69	0.60	0.37	1332	119	54	35	769	46
133		Cutting on crest of Tikitere Hill, 127 - 136 cm above base, (A,L).	N76/829134	4.96	0.64	0.56	0.27	1298	92	44	32	906	37
134		Northern Boundary Rd, 3 - 9 cm, (15 cm T), (A).	N86/941781	5.14	0.50	0.58	0.11	1466	62	59	39	743	63
135		Gavin Rd, Rerewhakaaitu, 2 - 8 cm above base, (14 cm T), (A).	N86/993831	5.09	0.48	0.71	0.12	1690	66	54	31	866	60
136		L. Rotoiti, Rotorua-Whakatane Highway, 185 - 197 cm above road level, (405 cm +), (L).	N77/945150	4.68	0.55	0.67	0.26	1489	80	54	35	1090	30
137		as above, 336 - 348 cm above road level (L).	" "	4.84	0.59	0.68	0.16	1607	94	53	31	1141	28
138		L. Rotoehu, Rotorua-Whakatane Highway, 52 - 59 cm above road level (213 cm +), (L).	N77/976164	5.13	0.61	0.75	0.25	1610	81	53	36	1037	28
139		as above, 122 - 127 cm above road level (L).	" "	5.19	0.57	0.72	0.17	1564	102	56	34	1058	23

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
140		as above, 188 - 195 cm above road level (L).	" "	5.46	0.53	0.64	0.11	1436	76	48	26	1146	40
R O T O M A A S H													
141		Democrat Rd, Rerewhakaaitu, (T.L.), basal 12 cm, (81 cm T), (A).	N86/934824	4.22	0.72	0.81	0.14	1403	37	45	45	1201	15
142		as above, 26 - 33 cm above base (A)	" "	4.28	0.74	0.75	0.09	1478	41	46	42	1010	17
143	11855	" " 36 - 40 cm " " "	" "	4.56	0.74	0.77	1.10	1483	30	44	32	1143	18
144		" " 46 - 50 cm " " "	" "	4.62	0.68	0.81	0.17	1474	35	49	51	1113	19
145	11856	" " 59 - 71 cm " " "	" "	5.22	0.60	0.64	0.15	1337	31	40	26	795	32
146		Gavin Rd, Rerewhakaaitu, 20 - 28 cm above base, (76 cm T), (A,L).	N86/993831	4.98	0.55	0.69	0.14	1347	64	45	25	989	24
147		Mt. Tarawera, gully SE Wahanga Dome basal 15 cm (50 cm T), (A,L).	N77/985942	4.81	0.70	0.74	0.13	1521	55	47	35	1248	22
148		Okiore, Opotiki-Matawai Rd, basal 6 cm (15 cm T), (A).	N78/716976	4.44	0.69	0.70	0.12	1497	33	49	31	1250	30
149		as above, 8 - 13 cm above base (A)	" "	4.63	0.67	0.76	0.09	1539	45	49	37	785	25
150		Matahina Rd, basal 10 cm (84 cm T) (A).	N86/060860	5.15	0.66	0.71	0.12	1408	68	66	28	639	27
151		[1]Kawerau, 500 m SE Roof Dome, basal 20 cm (90 cm T), (A,L).	N77/200086	5.18	0.69	0.80	0.21	1567	51	44	25	708	33
152		[1]as above, 45 - 52 cm above base, (L).	" "	5.31	0.69	0.75	0.23	1641	69	43	24	556	34
153		[1]" " 65 - 79 cm above base, (A).	" "	5.26	0.54	0.76	0.14	1771	73	51	47	1490	31
154		Iwatahi Gully, Napier-Taupo Highway, cream-cakes, basal 4 cm, (17 cm T), (A).	N103/735200	5.17	0.61	0.68	0.10	1784	61	56	37	562	44
O P E P E T E P H R A													
155	P28859	Taupo Pumice Pit, lower Tsg 17.	N94/587347	7.63	1.26	0.64	0.25	3052	107	69	112	287	47
156	P28858	" " " upper Tsg 17.	" "	7.64	0.87	0.65	0.16	3147	107	79	108	245	55

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
157	P28370	" " Tsg 18a.	" "	7.10	0.60	0.53	0.21	2929	70	67	89	526	49
158	11857	Napier-Taupo Highway, basal 30 cm (155 cm T), (L,B).	N94/572354	7.53	0.69	0.55	0.42	3603	115	71	91	210	51
159		[a]as above, 59 - 71 cm above base, (L).	" "	7.24	0.80	0.59	0.37	3470	117	69	87	226	59
160		as above, 100 - 109 cm above base, (L,B).	" "	6.60	1.27	0.63	0.15	3341	149	97	105	254	48
161		Iwatahi Gully, Napier-Taupo Highway, basal 15 cm (116 cm T), (L).	N103/735200	7.91	0.81	0.54	0.15	3225	132	93	105	183	75
162		as above, 80 - 98 cm above base, (A).	" "	7.11	0.70	0.59	0.24	3845	87	72	100	303	47
163		Road to Burrows Quarry, Tauhara, basal 8 cm (91 cm T), (L).	N94/647394	7.85	0.64	0.57	0.34	3564	79	68	89	467	41
164		Collin's Farm, southern side Waitahanui River, basal 10 cm, (56 cm T), (B).	N103/622142	7.13	0.88	0.51	0.16	3267	158	90	94	127	81
165		as above, 25 - 31 cm above base, (L).	" "	6.44	1.40	0.42	0.12	3495	110	138	119	156	90
		PORONUI TEPHRA											
166	P28368	Taupo Pumice Pit, Tsg 20.	N94/587347	6.97	0.62	0.46	0.24	3320	57	76	89	595	58
167	P28367	" " " Tsg 21.	" "	7.92	0.78	0.55	0.49	2809	74	67	92	400	-
168	P28366	" " " Tsg 22.	" "	7.81	0.76	0.61	0.18	3066	114	75	99	280	56
169		Collin's Farm, southern side Waitahanui River, basal 10 cm, (30 cm T), (L).	N103/622142	6.33	0.76	0.43	0.37	3495	131	72	107	138	75
170		as above, 10 - 15 cm above base, (L).	N103/622142	6.67	0.65	0.42	0.13	3680	175	92	111	278	63
171	11858	Road to Burrows Quarry, Tauhara, basal 12 cm (58 cm T), (A,L).	N94/647394	6.99	0.59	0.42	0.12	3791	200	88	111	151	68
172		Iwatahi Gully, Napier-Taupo Highway, basal 15 cm (33 cm T), (A,L).	N103/735200	7.02	0.67	0.47	0.24	3602	131	75	110	136	78
173		Napier-Taupo Highway, basal 15 cm (25 cm T), (A).	N94/572354	6.96	0.62	0.49	0.18	3542	112	80	109	158	65

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
174		Desert Rd, (2 cm T), (A).	N112/298951	6.25	0.90	0.52	0.23	2 804	113	82	99	497	59
175		^{f}Above Taupo-Turangi Road, (6 cm T), (A).	N102/341070	6.10	0.72	0.53	0.13	2960	102	76	90	584	-
176		^{f}Head of Waipakihi River, (8 cm T), (A).	N112/431846	8.78	0.75	0.38	0.08	3039	146	66	113	193	74
177		Tsg 19, Napier-Taupo Highway, sampled in paleosol on Poronui Tephra, (A).	N94/572354	6.10	1.49	0.44	0.79	3820	701	122	206	152	95
178		Tsg 19, Iwatahi Gully, Napier-Taupo Highway, sampled in paleosol on Poronui Tephra, (A).	N103/735200	5.39	1.47	0.38	0.46	4913	562	142	217	138	96
179		Tsg 19, road to Burrows Quarry, Tauhara, sampled in paleosol on Poronui Tephra, (A).	N94/647384	5.34	1.44	0.45	0.20	5356	596	149	214	86	119
180		Tsg 19, Collin's Farm, sampled in paleosol on Poronui Tephra, (A).	N103/622142	5.60	1.38	0.48	0.33	4139	419	120	178	144	101
			KARAPITI LAPILLI										
181	P28865	Taupo Pumice Pit, Tsg 23.	N94/587347	7.43	0.67	0.57	0.14	3090	111	76	114	350	50
182	P28864	" " " Tsg 24a upper.	" "	7.65	0.66	0.62	0.23	3236	103	74	154	379	49
183	P28863	" " " Tsg 24b lower.	" "	7.56	0.83	0.68	0.18	3723	131	79	135	266	53
184	P28862	" " " Tsg 25 upper.	" "	7.59	0.59	0.51	0.45	2912	68	74	105	529	54
185	11859	Road to Burrows Quarry, Tauhara, basal 15 cm, (36 cm T).	N94/647394	6.72	0.86	0.54	0.13	3924	150	76	106	163	55
186		as above, 18 - 26 cm above base, (A,L).	N94/647394	6.65	0.95	0.57	0.13	3640	191	78	110	205	55
187		Collin's Farm, southern side Waitahanui River, basal 15 cm, (28 cm T), (L).	N103/622142	6.63	0.78	0.56	0.13	3914	158	85	113	183	69
188		as above, basal 15 cm (A).	" "	7.11	0.83	0.56	0.14	3998	163	85	120	204	61
189		as above, 17 - 21 cm above base, (A,L).	" "	6.82	0.66	0.46	0.10	3722	129	72	119	208	66
190		as above, 23 - 26 cm above base, (A,L).	" "	7.21	0.80	0.54	0.11	3893	246	86	122	194	61

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
191		Iwatahi Gully, Napier-Taupo Highway, basal 6 cm, (10 cm T), (L).	N103/735200	6.92	0.87	0.54	0.10	3096	179	75	115	192	64
192		as above, paleosol 2 - 5 cm from base of Poronui Tephra.	" "	6.57	1.00	0.43	0.16	4363	475	104	176	204	91
193		Road to Burrows Quarry, Tauhara, 20 cm below base Karapiti.	N94/647394	5.94	1.47	0.45	0.10	5324	1464	126	244	201	66
194		Iwatahi 25 cm below base Karapiti Lapilli.	N103/735200	6.07	1.72	0.35	0.11	6702	2207	149	325	120	90
195	P28860	Taupo Pumice Pit, Tsg 26.	N94/587347	6.99	1.83	0.39	0.30	5572	1587	163	357	110	112
		WAIOHAU ASH											
196		Democrat Rd, Rerewhakaaitu (T.L.) basal 35 cm (216 cm T), (A,L).	N86/934824	4.53	0.83	0.78	0.10	1673	46	53	56	548	34
197	11860	as above, 87 - 96 cm above base, (L).	" "	4.84	0.94	0.72	0.36	1705	77	46	44	1068	19
198		as above, 114 - 125 cm above base, (A).	" "	5.28	0.71	0.60	0.16	1653	61	38	31	752	39
199		as above, 30 - 143 cm above base, (A,L).	" "	3.91	0.86	0.72	0.17	1491	55	44	50	1150	27
200		as above, 160 - 193 cm above base, (A,L).	" "	4.26	0.91	0.72	0.16	1614	61	51	63	1155	38
201	11861	as above, 199 - 211 cm above base, in paleosol, (A).	" "	5.51	0.84	0.67	0.14	1976	107	93	106	946	37
202		Gavin Road, Rerewhakaaitu basal, 15 cm, (178 cm T), (L).	N86/993831	4.51	0.79	0.71	0.23	1777	62	51	40	1377	30
203	11862	Okiore, Opotiki-Matawai Rd, basal 8 cm, (14 cm T), (A).	N78/716976	4.34	0.77	0.74	0.06	1674	52	54	46	1020	31
204		Waikaremoana Rd turn-off, Rotorua -Taupo Highway, basal 15 cm, (84 cm T), (L).	N85/840831	5.10	0.69	0.66	0.14	1765	74	32	27	876	44
205		[a]Cnr Gladstone-Grey St. - Gisborne, borehole ash at 17.68 - 17.83 m depth.	N98/402371	5.16	0.61	0.83	0.61	1654	55	51	52	338	36
206		[j]Waikaremoana-Wairoa State Highway No. 38.	N105/789028	6.38	0.60	0.81	0.15	1251	79	49	28	313	74

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
207	11863	Okiore, Opotiki-Matawai Rd, 11 - 14 cm above base, in paleosol, (A).	N78/716976	6.09	1.64	0.56	0.10	4600	538	111	185	237	108

ROTORUA ASH

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
208		Hemo Gorge, Rotorua-Taupo Highway, basal 15 cm (102 cm T), (B).	N76/714005	5.21	0.97	0.64	0.27	2325	131	55	43	430	40
209		Road W. side L. Rotorua, basal 25 cm (125 cm T), (B).	N76/676125	5.29	0.92	0.64	0.41	2398	143	48	43	453	43
210		Rotorua-Taupo Highway, basal 15 cm (71 cm T), (L).	N76/780908	4.21	0.98	0.59	0.63	2039	124	48	56	524	20
211		as above, 10 - 25 cm above base, (A,L).	" "	4.51	0.67	0.66	0.14	1946	141	44	58	743	23
212	11864	Lynmore Hill, quarry, basal 90 cm (5 m +), (B).	N76/771013	5.08	0.98	0.57	0.57	2652	176	68	80	311	22
213	11865	as above, 190 - 202 cm from top, (A,L).	" "	4.72	0.98	0.56	0.48	2292	142	62	67	683	18
214	11866	as above, 18 - 28 cm from top, (A).	" "	4.99	0.93	0.62	0.06	2364	161	75	67	639	22
215		Mamaku Plateau, Rotorua-Tirau Highway, basal 30 cm (59 cm T), (A,L).	N76/625122	4.64	0.98	0.57	0.19	2399	137	63	62	593	18
216		Palmer Rd ash overlying Puketarata Ash (18 cm T) 1 - 2 phi.	N94/542499	5.50	0.95	0.66	0.13	2383	353	102	89	283	66
217		" " " 2 - 2.75 phi.	" "	5.50	0.72	0.67	0.15	2135	148	72	64	680	32
218		" " " 2.75 phi.	" "	5.68	0.90	0.72	0.15	2268	209	84	64	470	42
219		Cutting on crest of Tikitere Hill, Rotorua-Whakatane Highway, basal 8 cm (38 cm T), (A).	N76/829134	5.11	0.82	0.67	0.17	1950	186	74	71	781	48

PUKETARATA ASH

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
220		Palmer Rd, basal 9 cm (50 cm T), (A,L).	N94/542499	6.20	0.44	0.66	0.09	1758	151	51	54	244	58

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
221		as above, 25 - 32 cm above base, (A).	" "	5.45	0.56	0.68	0.11	2136	245	54	66	233	63
222		Wairakei-Putaruru Highway (T.L.) basal 30 cm (457 cm + T), (L).	N94/516544	6.35	0.52	0.77	0.45	2530	166	69	87	334	63
223		as above, 25 - 40 cm from top, (A,L).	" "	6.39	0.43	0.78	0.50	1936	179	82	79	435	56
		REREWHAKAAITU ASH											
224		Democrat Rd, Rerewhakaaitu, (T.L.) basal 15 cm (146 cm T), (A).	N86/934824	4.79	0.61	0.71	0.11	2122	149	58	67	733	41
225	11872	Democrat Rd, 28 - 40 cm above base, (A,L).	" "	4.50	0.85	0.70	0.50	2058	167	57	60	871	32
226		" " 46 - 61 cm " " (A).	" "	5.08	0.61	0.75	0.10	2179	160	72	63	1061	35
227	11871	" " 82 - 96 cm " " (A,L).	" "	4.62	0.62	0.65	0.08	1990	134	64	55	1223	26
228	11870	" "127 - 141 cm " " 1 phi.	" "	4.64	0.68	0.70	0.16	2011	259	83	87	703	42
229	11869	" " " " " " 1 - 2 phi.	" "	5.28	0.80	0.87	0.18	2329	268	79	87	591	35
230	11868	" " " " " " 2 phi.	" "	6.30	1.19	0.64	0.15	3629	443	184	205	465	132
231		Matahina Rd, Rerewhakaaitu basal 15 cm (128 cm T), (A,L).	N86/060860	4.73	0.76	0.60	0.50	1942	232	62	48	567	47
232		Gavin Rd, Rerewhakaaitu, basal 18 cm (116 cm T), phenocryst rich blocks.	N86/995824	5.34	0.45	0.62	0.24	1920	151	35	33	684	20
233		as above, Rerewhakaaitu, basal 18 cm phenocryst poor blocks.	" "	4.83	0.64	0.60	0.24	1404	45	36	21	732	24
234		Mt. Tarawera, gully SE Wahanga Dome, basal 25 cm.	N77/988948	5.44	0.71	0.65	0.40	1640	149	60	44	466	44
235		Palmer Rd, underlying Puketerata Ash, basal 10 cm (20 cm T), (A).	N94/542499	5.42	0.56	0.84	0.08	2616	175	46	71	392	41
236		f Mangetepopo Valley, on moraine, (4 cm T), (A).	N112/089823	5.06	0.54	0.70	0.09	2245	142	53	46	451	34

OKAREKA ASH

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
237		Rotorua-Taupo Highway, basal 10 cm (51 cm T), (A,L).	N76/780908	4.18	0.70	0.60	0.06	1934	135	54	60	516	29
238	11873	Gavin Rd, basal 8 cm (23 cm T), (A).	N86/995824	4.91	0.62	0.62	0.11	2340	151	60	50	758	36
TE RERE ASH													
239		Rotorua-Taupo Highway, basal 8 cm, (53 cm T), (A,L).	N76/780908	4.40	0.95	0.65	0.06	1734	57	51	49	545	17
240	11874	Gavin Rd, basal 6 cm, (31 cm T), (A,L).	N86/995824	5.26	0.78	0.78	0.14	1625	68	49	38	764	46
ORUANUI FORMATION													
241	11875	Wairakei-Putaruru Highway, (T.L.), basal 30 cm, (518 cm T), (L).	N94/523521	6.17	0.62	0.44	0.16	2714	195	75	69	184	36
242	11876	as above, 38 - 68 cm, above base, (A).	" "	6.26	0.68	0.47	0.23	2636	180	73	64	159	27
243		as above, 112 - 137 cm, above base, (A).	" "	5.26	1.09	0.51	0.11	3320	425	106	221	132	72
244		as above, 143 - 148 cm, above base, (A).	" "	6.14	0.52	0.62	0.09	2834	161	66	75	147	34
245	11877	as above, 181 - 204 cm, above base, chalazoidites (A).	" "	6.07	0.79	0.49	0.14	3046	427	84	102	124	34
246		Napier-Taupo Highway, chalazoidites at base of section, (A).	N94/571355	5.93	0.76	0.52	0.45	2662	301	70	81	397	44
247		Gavin Rd, 23 - 28 cm above base, chalazoidites, (A).	N86/995824	6.08	0.68	0.52	0.07	2773	280	72	88	207	60
248		as above, basal 8 cm, (64 cm T), (A,L).	" "	6.68	0.64	0.49	0.10	2948	254	68	77	221	43
249	11878	Braemar Road, 2 - 10 cm above base, (30 cm T), (A).	N68/202265	5.30	0.80	0.55	0.11	2963	261	90	115	391	95

ANALYSIS No.	SAMPLE No.	L O C A T I O N	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
250		Waihua Beach basal 45 cm, (A).	N115/689868	5.36	0.77	0.45	0.59	2260	140	72	71	120	31
251		Collin's Farm, 33 - 45 cm from top, (L).	N103/622142	5.26	0.78	0.63	0.57	2535	168	63	74	253	71
252		Tumunui Rd, bed 2, basal 10 cm.	N76/773905	5.16	0.63	0.44	0.12	2932	139	75	86	386	35
253		Taumarunui-Turangi Rd, (A).	N102/002129	5.74	0.81	0.40	0.13	3618	252	84	118	348	29
254		[f]Rangipo Desert, (A).	N122/175575	6.47	1.01	0.51	0.30	3292	250	85	109	223	70
255		[f]Desert Rd - <u>Hinuera Formation</u>	N112/299950	5.31	0.79	0.61	0.59	2079	146	70	70	313	56
256		5 km south of Waipukarau - basal 10 cm, (36 cm T), (A), <u>Aokautere Ash.</u>	N146/006727	5.65	0.81	0.50	0.48	2271	202	64	76	594	45
257	11880	Cutting outside Massey Univ., basal 6 cm, (13 cm T), (A), - <u>Aokautere Ash.</u>	N149/106316	6.27	0.82	0.45	0.43	2666	302	74	87	122	48
258		Ormondville-Whetukura Rd, basal 2 cm, (28 cm T), (A,L), - <u>Aokautere Ash.</u>	N145/717638	6.17	0.73	0.52	0.58	2374	119	74	81	535	31
259		as above, 4 - 7 cm above base, (A).	" "	5.80	0.75	0.50	0.42	2662	196	86	97	453	46
260		as above, 8 - 14 cm above base, (A).	" "	5.22	0.75	0.48	0.49	2565	217	85	98	461	52
261		as above, 15 - 22 cm above base, (L).	" "	5.25	0.71	0.47	0.50	2321	174	80	79	416	28
262		[k]Matawhero Rd, south side Rangitikei River, 12 - 18 cm above base, (39 cm T), (A,L), - <u>Aokautere Ash.</u>	N133/505316	6.40	0.77	0.48	0.23	2251	234	67	64	401	26
263		[k]Matawhero Rd, 19 - 33 cm above base, (A) - chalazoidites.	N133/505316	5.70	0.88	0.53	0.17	2523	305	66	84	479	48
264		NE side Tongariro River, <u>Oruanui Breccia</u> Upper.	N102/303015	6.11	0.71	0.70	0.64	3109	284	86	123	400	49
265		" " "	N102/303015	5.78	0.75	0.63	0.86	3559	239	72	100	418	63
266		[m]Taupo-Wairakei Highway - outside Wairakei Hotel - <u>Oruanui Breccia</u>, (A,L).	N94/560445	5.16	0.82	0.55	0.75	2117	232	72	74	425	50
266a	P30399	0.6 km E of Pohipi Rd - <u>Wairakei Breccia.</u>	N94/533436	5.50	0.77	0.53	0.32	2762	258	85	97	282	37

MANGAONE LAPILLI FORMATION

MEMBER E

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
267	11881	Braemar Rd, basal 40 cm, (152 cm T), (B).	N68/202265	5.08	0.80	0.76	0.08	1074	22	30	26	645	25
268	11882	as above, 96 - 112 cm above base, (A,L).	" "	4.98	0.95	0.78	0.06	1414	22	45	38	431	42
269	11883	as above, 131 - 143 cm above base, in paleosol,	" "	5.08	1.14	0.65	0.07	2810	105	91	95	386	50
270		aPutauaki Forest, basal 15 cm, (L,B).	N77/153058	5.07	0.72	0.73	0.10	1246	21	43	28	718	25
271		Matahina Rd, basal 13 cm, (242 cm T), (B).	N86/096874	5.41	0.75	0.98	0.06	915	43	33	30	812	48
272		as above, 140 - 153 cm above base, (L).		5.65	0.87	0.89	0.08	1979	72	51	60	258	32
273		as above, 191 - 201 cm above base, (A,L).		5.04	0.76	0.75	0.04	1356	35	43	46	351	43
274		Kukumoa, Whakatane-Opotiki Highway, basal 20 cm, (94 cm T), (B).	N78/693195	5.31	0.79	0.75	0.16	767	16	15	12	973	30

MEMBER D

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
275	11885	Braemar Rd, basal 9 cm, (33 cm T), (A,L).	N68/202265	4.68	0.80	0.81	0.08	1064	17	33	28	734	21
276	11886	as above, 10 - 20 cm above base, (A,L).	" "	4.76	0.76	0.78	0.06	1021	15	27	33	1105	18
277	11887	as above, 23 - 28 cm above base, (A,L).	" "	4.96	0.94	0.73	0.07	1625	22	55	24	895	37

MEMBER C

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
278	11892	Braemar Rd, basal 30 cm, (249 cm T), (B).	N68/202265	5.11	0.88	0.73	0.12	1179	20	41	24	692	20

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
279	11893	as above, 180 - 188 cm above base, (L,B).	" "	4.73	0.95	0.78	0.10	1356	45	46	59	587	28
280	11894	as above, 237 - 244 cm above base, in paleosol, (A,L).	" "	4.43	1.06	0.69	0.13	1649	37	58	44	284	22
281	11895	Tumunui Rd, basal 23 cm.	N76/773905	4.75	0.87	0.61	0.07	1486	23	49	35	309	23
282		" " 38 - 58 cm from top.	" "	5.11	0.87	0.68	0.05	1592	24	49	37	386	27
283	11896	" " 3 - 9 cm from top paleosol.	" "	4.91	1.45	0.60	0.07	2859	80	130	100	188	57
284		Matahina Rd, basal 10 cm, (140 cm T), (B).	N86/096874	5.45	1.12	0.82	0.15	1680	75	51	42	367	33
285		as above, 71 - 84 cm from top.	" "	5.16	1.00	0.91	0.10	1829	72	53	55	583	40
286		Kukumoa, Whakatane-Opotiki Highway, basal 24 cm, (135 cm T), (B).	N78/693195	5.05	0.85	0.77	0.18	922	15	22	14	992	30
287		Whakatane-Chope Rd, basal 30 cm.	N69/450243	5.24	0.84	0.77	0.20	966	14	16	16	700	29
288		Waipaoa, Gisborne Plains, basal 23 cm.	N98/286522	4.55	0.73	0.71	0.09	830	13	29	16	1087	18
289		as above, 5 - 15 cm from top.	" "	4.56	1.02	0.72	0.10	1354	92	57	39	658	23
290		" " paleosol of Rotoehu Ash.	" "	4.97	0.88	0.68	0.10	1402	21	39	28	706	20
291		[j]Te Mata Peak.	N134/316142	6.30	0.68	0.68	0.21	755	74	52	42	744	66
292		Ormond's Quarry, near L. Rotoiti, basal 30 cm, (427 cm T), (B).	N76/855144	4.67	0.80	0.74	0.41	1077	15	39	63	1049	42
293		Rotorua-Whakatane Highway, Moose Lodge, Hauparu Bay, L. Rotoiti.	N76/876151	4.03	0.60	0.73	0.06	1474	28	40	69	1356	25

MEMBER B - 2

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
294		Tumunui Rd, 20 cm above base.	N76/773905	4.71	1.26	0.70	0.13	2578	82	104	77	136	50
295		as above, basal 10 cm.	" "	4.29	1.27	0.63	0.09	2576	130	97	84	145	41
296	11899	Braemar Rd, basal 20 cm, (127 cm T), (B).	N68/202265	4.89	1.25	0.59	0.14	2512	63	79	76	77	24
297		as above, basal 20 cm, (A,L).	" "	5.23	1.30	0.55	0.19	2687	90	79	80	100	19
298	11900	as above, 51 - 66 cm above base, (A,L).	" "	4.86	1.62	0.54	0.12	2436	64	83	69	75	31

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
299	11897	as above, 109 - 124 cm above base, (A,L).	" "	5.13	1.08	0.59	0.07	2485	51	79	60	117	19
300		Matahina Rd, basal 23 cm, (L).	N86/096874	5.24	1.33	0.68	0.07	2281	59	61	59	50	39
		MEMBER B - 1											
301	11901	Braemar Rd, basal 15 cm, (183 cm T), (B).	N68/202265	5.24	1.36	0.61	0.58	1880	25	77	48	71	24
302	11902	as above, 147 - 158 cm above base, (B).	" "	5.54	1.43	0.60	0.33	1708	24	68	52	69	20
303		as above, 147 - 158 cm above base, (A,L).	" "	5.07	1.33	0.61	0.37	1859	16	70	43	63	20
304	11903	as above, 168 - 177 cm above base, in paleosol, (A).	" "	5.38	1.37	0.64	0.15	1973	32	79	56	99	29
305		Hairini, basal 20 cm, (A,L).	N58/645548	4.98	1.54	0.66	0.21	1696	26	61	39	84	20
306		William's Track, basal 12 cm, (A,L).	N67/843353	4.88	1.55	0.70	0.47	1709	33	62	42	61	20
307		Matahina Rd, basal 15 cm (L).	N86/096874	5.73	0.99	0.60	0.14	1462	38	54	32	63	42
		MEMBER A											
308	11906	Braemar Rd, basal 10 cm, (66 cm T), (A,L).	N68/202265	4.51	0.75	0.40	0.14	3522	271	97	110	280	19
309	11905	as above, 18 - 26 cm above base, (A).	" "	4.63	0.73	0.42	0.14	3531	241	88	106	323	21
310	11907	as above, 32 - 56 cm above base, in paleosol, (A).	" "	5.07	1.20	0.48	0.10	3059	141	95	91	165	25
311	11904	Matahina Rd, basal 15 cm, (L).	N86/096874	4.68	0.73	0.38	0.18	3457	228	121	106	398	22
312		Tumunui Rd, pink ash, (A).	N76/733905	5.10	0.71	0.43	0.19	3590	255	104	116	439	27
313		as above, paleosol, (A).	" "	5.04	1.24	0.54	0.09	3308	194	124	118	323	55

EARTHQUAKE FLAT BRECCIA FORMATION

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	C o	Ni	Zr	Cu
314	15007/3a	^{m}Near Tumunui Rd, airfall tephra, basal Earthquake Flat Breccia.	N85/716891	4.59	0.60	0.58	0.52	2474	235	71	76	489	22
315	15005/3a	^{m}Rotorua-Taupo Highway, airfall tephra overlying Earthquake Flat Breccia.	N76/783903	5.97	0.58	0.54	0.27	2527	220	60	63	354	36
316		as above, Rifle Range ash, 35 - 42 cm.	N86/125658	5.44	0.48	0.68	0.12	2904	212	72	86	877	46
317		Rotorua-Murupara Highway, Rifle Range ash, 64 - 69 cm from top.	" "	5.04	0.49	0.73	0.12	2773	185	68	72	607	41
318	15009a	^{m}Maleme Rd, Rifle Range ash.	N85/598781	4.81	0.57	0.62	0.11	2501	177	67	63	1097	24
319		^{m}Butcher Rd, Rifle Range ash.	N85/751669	6.07	0.47	0.56	0.03	2321	160	64	80	342	33
320		Waihua Beach, Rifle Range ash, top 8 - c. 18 cm, (of Rotoehu Ash).	N115/639868	4.66	0.67	0.61	0.30	2421	166	73	71	205	25
321	15005/1	^{m}Rotorua-Taupo Highway, Earthquake Flat Breccia.	N76/783903	5.70	0.55	0.59	0.49	2407	226	68	60	563	38

ROTOITI BRECCIA FORMATION

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	C o	Ni	Zr	Cu
322	15018a	^{m}Saunders Track, basal grey shower-bedded Rotoehu Ash at base of flow deposits.	N67/818347	4.29	0.76	0.71	0.13	2395	75	60	56	143	15
323	15020a	^{m}Saunders Track, shower-bedded Rotoehu Ash, 90 cm from base of Rotoiti Breccia Formation.	N67/818347	4.48	0.77	0.71	0.10	2468	84	77	59	74	14
324	15022a	^{m}Maleme Rd, Rotoehu Ash under Rifle Range ash.	N85/598781	3.89	0.74	0.65	0.10	2269	63	74	61	612	17
325		Kawerau Rubbish Dump, basal shower-bedded Rotoehu Ash.	N77/160090	4.27	0.71	0.72	0.77	2578	67	76	72	311	27
326		Waihi Beach, basal 20 cm, Rotoehu Ash.	N53/434880	4.06	0.73	0.69	0.11	2260	61	60	52	440	17
327	11908	Kukumoa, basal 45 cm, (127 cm T), (A), Rotoehu Ash.	N78/693195	4.60	0.70	0.64	0.17	2108	46	55	36	551	25

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
328		Hairini, basal 15 cm of Rotoehu Ash.	N58/645548	4.08	0.65	0.59	0.11	2180	54	63	58	568	16
329		" 97 - 115 cm (from top), Rotoehu Ash.	" "	4.08	0.69	0.69	0.13	2301	59	61	56	579	18
330	11911	" 4 - 20 cm (from top), " " in paleosol.	" "	4.29	0.81	0.69	0.09	2431	76	88	74	357	27
331		Waihua Beach, 74 - 90 cm Rotoehu Ash.	N115/689868	4.07	0.72	0.59	0.13	2261	63	81	58	77	14
332		Waituhi.		4.05	0.74	0.65	0.05	1962	79	58	52	167	15
333		Matahina Rd, basal 10 cm, Rotoehu Ash.	N86/055859	5.01	0.71	0.74	0.54	2435	73	59	44	499	29
334	11909	Braemar Rd, 56 - 70 cm (from top) Rotoehu Ash.	N68/202265	4.43	0.66	0.65	0.14	2309	81	62	57	430	22
335	11910	as above, 3 - 18 cm " " Rotoehu Ash (in paleosol).	" "	4.41	0.73	0.61	0.13	2481	91	74	64	320	21
336	15017a	[m]William's Track, shower-bedded Rotoehu Ash overlying Rotoiti Breccia.	N67/843353	4.44	0.75	0.69	0.09	2534	85	79	58	97	21
337	15012	[m]Saunders Track, Rotoiti Breccia flow unit, 46 cm above basal shower-bedded Rotoehu Ash.	N67/818347	3.93	0.69	0.74	0.09	2400	56	64	57	454	26
338	15010	[m]William's Track, 60 - 80 cm from top of Rotoiti Breccia.	N67/843353	4.22	0.75	0.65	0.14	2265	84	64	60	303	22
339		Ormond's Quarry, Rotoiti Breccia, (B).	N76/854147	4.38	0.63	0.59	0.88	1908	57	57	40	530	33
340		as above, Rotoiti Breccia, (A).	" "	4.29	0.71	0.65	1.08	1818	72	58	35	501	42
341		Kawerau Rubbish Dump, Rotoiti Breccia.	N77/160090	4.52	0.69	0.66	0.26	2056	55	54	44	408	27
342	15014	[m]Whaka Forest, Rotoiti Breccia.	N76/753003	4.42	0.70	0.69	0.42	2260	76	66	61	302	25
343	15013	[m]Haumi Stream, "pisolitic breccia"	N85/869857	4.28	0.76	0.74	0.58	2245	77	68	60	147	21

APPENDIX III

RHYOLITIC TEPHRA MARKER BEDS IN THE TONGARIRO AREA, NORTH ISLAND, NEW ZEALAND

This appendix contains the main part of a manuscript accepted for publication in N.Z. Journal of Geology and Geophysics.

RHYOLITIC TEPHRA MARKER BEDS IN THE TONGARIRO AREA, NORTH ISLAND, NEW ZEALAND

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ABSTRACT

In the Tongariro area 13 rhyolitic tephras erupted from Okataina, Maroa and Taupo Volcanic Centres over the last 20,000 years are interbedded with local andesitic tephras. The order of succession of the 13 tephras is established by stratigraphy, and is confirmed by their mineralogical composition and by chemical analysis of their titanomagnetites. Seven of the rhyolitic tephras have been previously dated by ^{14}C , four are dated here, and two are not yet dated. The four new ^{14}C dates provide ages of c. 12,500 yrs B.P. for Rotorua Ash (N.Z. 1186, N.Z. 1187); 9,785±170 yrs B.P. for Papanetu Tephra and Karapiti Lapilli (N.Z. 1372, N.Z. 1374); and c. 9,740 yrs B.P. for Poronui Tephra.

INTRODUCTION

Andesitic tephras erupted from the Tongariro National Park volcanoes (Fig 1) have been studied during the course of regional geological mapping (Grange and Hurst 1929; Grange and Williamson 1930; Gregg 1960) and soil mapping (Grange 1931; Grange and Taylor 1931; New Zealand Soil Bureau 1954). Only the youngest tephras have been formally named and mapped in any detail. Ngauruhoe Ash (Grange and Hurst 1929, p. 6) was mapped by Grange (1931) as a soil-forming ash and includes all andesitic ash from the Tongariro Volcanic Centre (Grindley 1960) above the rhyolitic Taupo Pumice (Baumgart 1954; Healy 1964). Gregg (1960) formally named the Mangatawai Ash for ... "thinly bedded dark-grey andesite ash containing leaves " .... (Grange and Hurst 1929, p. 7) immediately underlying Taupo Pumice. Tongariro Ash was a comprehensive name for andesitic tephra older than Mangatawai Ash (Gregg 1960, p. 38).

Individual beds within the Tongariro Ash are "confusingly alike" (Gregg 1960, p. 38). Where stratigraphic sections are close together, the andesitic tephras can be correlated without difficulty. But where sections are more than 0.5 km apart the similarity in appearance and complex distribution pattern of andesitic lapilli units makes correlation difficult.

The only rhyolitic tephras previously identified within the Tongariro tephra sequence have been Taupo Pumice (Baumgart 1954; Healy 1964) and Oruanui Formation (Vucetich and Pullar 1969). Gregg (1960) noted that other rhyolitic tephras occurring within the andesitic sequence may correlate with Taupo Subgroup members.

Twelve rhyolitic tephras of known age have now been identified within the andesitic tephra sequence and have proved to be very useful marker beds. Most sections within the Tongariro area contain at least one rhyolitic tephra and up to seven may be present in any one section. Eight rhyolitic tephras are widespread and useful as markers. The widespread rhyolitic tephras also provide valuable time control in the southern part of the study area where tephras from Ruapehu are dominant and where tephras from Tongariro are absent. A further

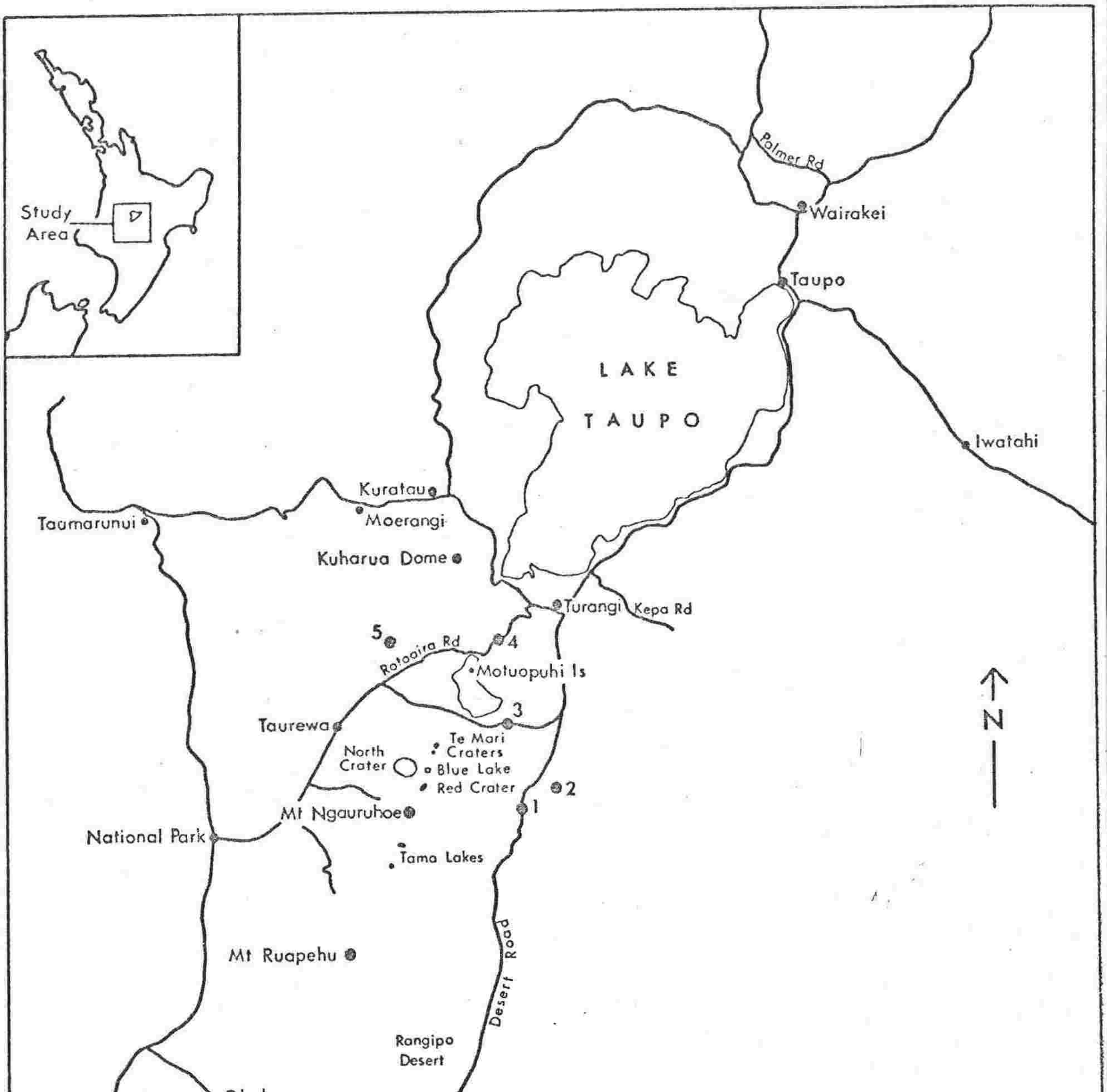

Fig. 1. - Locality map of study area. Numbers refer to reference sections: 1. Mangatawai; 2. Access 10; 3. Poutu; 4. Te Ponanga Saddle; and 5. Wairoa.

five rhyolitic tephras are present in the area but appear in too few sections to be of much value. However, the stratigraphic position of these less common tephras adds further time control to the otherwise difficult andesitic sequence.

North of Tongariro identification of rhyolitic tephras can be made from their stratigraphic position in relation to prominent andesite lapilli beds (Table 1). In the laboratory, identification of rhyolitic tephras has been determined by: radiocarbon dating of associated organic matter, heavy mineral determinations and the chemical analysis of titanomagnetites within tephra (Kohn 1970).

The identification of rhyolitic tephras provides a time-stratigraphic column (summarised in Table 1) for tephras in the Tongariro area. The established chronology therefore allows dating of other important late Quaternary events.

IDENTIFICATION AND CORRELATION OF RHYOLITIC TEPHRAS

Radiocarbon Dating:

Seven new radiocarbon dates from sites northwest of Tongariro provide ages for four rhyolitic tephras not previously dated. Papanetu Tephra, bracketed by two radiocarbon dates (N.Z. 1372, N.Z. 1374; Table 2), is assigned an age of 9,785 yrs B.P. Papanetu Tephra was erupted immediately following eruption of Karapiti Lapilli (Vucetich and Pullar 1973) and therefore the age of Karapiti Lapilli is also about 9,785 yrs B.P. An ash considered to be Rotorua Ash (Vucetich and Pullar 1964) is bracketed by two radiocarbon dates (N.Z. 1187, N.Z. 1186; Table 2) and is estimated to be 12,500 yrs B.P.

Two wood samples from peat in a swamp cut by the Otamangakau Canal (N112/109984) which underlie Taupo Pumice, and the age of the pumice itself, indicate that the peat accumulated uniformly at approximately 0.45 m/1000 years. The rate is used to date two interbedded tephras and one basal tephra not previously dated. The results are shown below:-

FORMATION	NAMED MEMBERS	UNNAMED BEDS	SYMBOLS	VOLCANIC CENTRE (SOURCE)	INFERRED STRATIGRAPHIC AGE (NOT ^{14}C-DATED)	^{14}C AGES IN YEARS BEFORE 1950	N.Z. ^{14}C NUMBER
[1]Ngauruhoe Tephra			ng	Tongariro			
[2]Taupo Pumice	Upper Taupo Pumice		tp 1	Taupo		1,819 ± 17	Averaged from many dates (Healy 1964)
	Taupo Lapilli		tp 3				
	Rotongaio Ash		tp 4				
	'Putty Ash'		tp 5				
[3]Mangatawai Tephra			mg	Tongariro		2,500 ± 200 (basal 80 mm)	N.Z. 186
		Andesitic tephra					
[4]Whakaipo Tephra			wo	Taupo		2,670 ± 50 (above ash) 2,730 ± 60 (below ash)	N.Z. 1070 N.Z. 1071
	-	Andesitic tephra					
[2]Waimihia	Waimihia Lapilli		wm	Taupo		3,170 ± 80 (above ash) 3,440 ± 80 (below ash)	N.Z. 504 N.Z. 505
[5]Papakai Tephra			pp	Tongariro			
[4]Hinemaiaia Ash			hn	Taupo		6,390 ± 120 (above ash) 6,190 ± 70 (below ash)	N.Z. 1137 N.Z. 1247
[5]Papakai Tephra			pp	Tongariro			
[6]Rotoma Ash			rm	Okataina		7,330 ± 235	N.Z. 1199
[5]Papakai Tephra			pp	Tongariro			
[4]Opepe Tephra			op	Taupo		8,850 ± 1000	N.Z. 185
[5]Papakai Tephra			pp	Tongariro			
[5]Mangamate Tephra	Poutu Lapilli		pt	Tongariro	9,700		
		Andesitic tephra		Tongariro			
[4]Poronui Tephra			po	Taupo	9,740		
[5]Mangamate Tephra		Andesitic tephra		Tongariro			
	Te Rato Lapilli		tt	Tongariro		9,700 ± 200 (below lapilli) 9,780 ± 170 (" ")	N.Z. 1372 N.Z. 1373
Papanetu Tephra			pa	Taupo	9,785		
[4]Karapiti Lapilli			kp	Taupo	9,790		
[5]Okupata Tephra		Unnamed ash Basal lapilli	oa	Tongariro		9,790 ± 160 (above ash)	N.Z. 1374
		Andesitic tephra		Tongariro			
[6]? Rotorua Ash			rr	Okataina	12,500	12,350 ± 220 (above ash) 13,150 ± 300 (below ash)	N.Z. 1187 N.Z. 1186
		Andesitic tephra		Tongariro			
[7]? Puketarata Ash			pk	Maroa	13,500		
		Andesitic tephra		Tongariro			
[5]Rotoaira Lapilli			rt	Tongariro		13,800 ± 300 (below lapilli)	N.Z. 1559
		Andesitic tephra		Tongariro			
[6]Rerewhakaaitu Ash			rk	Okataina		14,700 ± 200 (below ash)	N.Z. 716
		Andesitic tephra		Tongariro			
[8]Oruanui Formation	Oruanui Breccia		ou	? Maroa			
	Oruanui Ash					20,670 ± 300 (within ash) 19,850 ± 310 (below ash)	N.Z. 12 N.Z. 1056

1 Named by Grange & Hurst (1929)
2 " " Baumgart (1954)
3 " " Gregg (1960)
4 " " Vucetich & Pullar (1973)
5 Named by Topping (1973)
6 " " Vucetich & Pullar (1964)
7 " " Lloyd (1972)
8 " " Vucetich & Pullar (1969)

Table 1. - Stratigraphic column showing the relationship, in the Tongariro area, of andesitic tephras of the Tongariro Sub-group with interbedded rhyolitic tephras erupted from the Okataina, Maroa and Lake Taupo Volcanic Centres.

Tephra	Ages from rate of peat accumulation	Previous dates
Rotoma Ash (Vucetich & Pullar 1964)	7,430 yrs B.P.	7,330 yrs B.P. (Pullar & Heine 1971)
Opepe Tephra (Vucetich & Pullar 1973)	8,600 yrs B.P.	8,850 yrs B.P. (Healy 1964)
Poutu Lapilli (Topping 1973)	9,700 yrs B.P.	——

Poronui Tephra (Vucetich and Pullar 1973) lies between Poutu Lapilli and Papanetu Tephra so that its age is estimated to be 9,740 yrs B.P.

Ferromagnesian Assemblages and Chemical Analysis of Titanomagnetites:

Rhyolitic tephras of the Taupo Subgroup (Healy 1964) contain a ferromagnesian assemblage of dominantly hypersthene with or without (±) augite with very rare hornblende, biotite and olivine (Ewart 1963).

The Rotorua Subgroup tephras (Vucetich and Pullar 1964) include three different ferromagnesian assemblages (Ewart 1966; Cole 1970, and Table 2, p.   ), i.e.

(a) hypersthene ± augite
(b) hypersthene + calcic-hornblende ± cummingtonite, and
(c) biotite + hypersthene ± calcic-hornblende ± traces of augite.

The Oruanui Formation erupted from north of Lake Taupo (Vucetich and Pullar 1969) contains a ferromagnesian assemblage of hypersthene + calcic hornblende ± sparse augite ± rare biotite.

Taupo Subgroup tephras (i.e. erupted from Taupo Volcanic Centre), in containing very rare biotite and calcic-hornblende, can generally be distinguished from tephras erupted from other sources. But the uniformity of the ferromagnesian assemblage

FOSSIL RECORD NO. N.Z. ^{14}C NO.	^{14}C AGE YEARS B.P.(1950)	EVENTS AGED	SAMPLE DESCRIPTION; STRATIGRAPHIC POSITION	LOCALITY (N.Z.M.S. 1 (1968))*
N112/544 N.Z. 1336	3,200 ± 50	Provides check on rate of accumulation of peat and thus a more accurate estimate of age of Poutu Lapilli	Wood: within peat; 0.66 m below base of Taupo Pumice, 3.46 m above Poutu Lapilli	Tongariro, N112/109984; swamp cut by Otamangakau Canal, Tongariro Power Scheme
N112/545 N.Z.1335	9,560 ± 100	Minimum age for Poutu Lapilli	Wood: small branches from peat 4.03 m below Taupo Pumice and 90 mm above Poutu Lapilli	"
N112/551 N.Z. 1373	9,700 ± 210	Maximum for Te Rato Lapilli; minimum for Papanetu Tephra and Karapiti Lapilli	Peat: 5 mm horizon below Te Rato Lapilli and above Papanetu Tephra	Tongariro, N112/145983; swamp cut by Wairehu Canal, Tongariro Power Scheme. Approx. 0.9 km NW of point where Rotaira Road crosses canal
N112/550 N.Z. 1372	9,780 ± 170	"	Wood: twigs from 5 mm horizon of peat separating Te Rato Lapilli from the underlying Papanetu Tephra	"
N112/552 N.Z. 1374	9,790 ± 160	Maximum for Papanetu Tephra	Wood: twigs from 20 mm of peat below Papanetu Tephra	"
N112/539 N.Z. 1187	12,350 ± 220	Provides a minimum age for ? Rotorua Ash	Charcoal: scattered throughout 0.15 m andesitic tephra which in neighbouring sections immediately overlies ? Rotorua Ash	Tongariro: N112/105987; 450 m east of C Wairoa Trig, 90 m west of Tongariro Power Scheme Access Road No. 4
N112/540 N.Z. 1186	13,150 ± 300	Provides a maximum age for ? Rotorua Ash	Charcoal: scattered throughout top third of an andesitic tephra unit which in neighbouring sections is 0.13 m below ? Rotorua Ash	"
N112/548 N.Z. 1559	13,800 ± 300	Maximum age for Rotoaira Lapilli	Charcoal: within andesitic tephra immediately underlying Rotoaira Lapilli Formation	Tongariro: N112/298951; cutting on eastern side of Desert Road, east of Pihanga and 6.4 km south of Turangi

* All samples collected by W.W. Topping

Table 2. - ^{14}C ages for rhyolitic tephras present in the Tongariro area and associated andesitic tephras.

does not allow identification of individual formations (Table 3). The chemical analysis of titanomagnetites (Kohn 1970) was used to distinguish younger and older Taupo Subgroup tephras and also to confirm correlation of rhyolitic tephras from other centres.

Rhyolitic tephras sampled for chemical and mineralogical analysis were taken from the middle of pockets and lenses and were considered to be least contaminated.

Hypersthene ± augite	Hypersthene + calcic-hornblende ± cummingtonite	Biotite + hypersthene ± calcic-hornblende ± augite
Taupo Pumice	Oruanui Formation (may contain augite)	? Rotorua Ash
Whakaipo Tephra		? Puketarata Ash
Waimihia Lapilli	? Rotoma Ash (contains biotite where sampled in Tongariro region)	Rerewhakaaitu Ash
Hinemaiaia Ash		
Opepe Tephra		
Poronui Tephra		
Papanetu Tephra		
Karapiti Lapilli		

Table 3. - Dominant ferromagnesian assemblages for rhyolitic tephras identified in the Tongariro Volcanic Centre.

Titanomagnetite analyses are presented in Table 4.

Table 4. - Titanomagnetite analyses of rhyolitic tephras from near source and within the Tongariro area. All analyses are in ppm unless otherwise indicated. Analyses were carried out at Spectrographic Section, Chemistry Division, D.S.I.R., using apparatus and operating conditions described by Kohn (1970). Analyses are the averaged result of samples generally run in triplicate. The analytical precision, expressed as a relative deviation, was approximately ± 10%.

*Numbers prefixed by "P" belong to the petrological collection of the N.Z. Geological Survey.

RHYOLITIC TEPHRA

Analysis No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
1	Taupo Pumice	Napier-Taupo Highway basal 30 cm	N94/564354	7.92	1.06	0.69	0.54	649	131	16	27	68	22
2	Taupo Pumice	Wairakei-Putaruru Highway (Route 1)	N94/516544	7.92	0.69	0.80	0.66	847	117	35	55	83	43
3	Taupo Pumice	Old Ketatahi Track	N112/133894	7.63	0.89	0.92	0.77	968	162	50	55	78	68
4	Taupo Pumice	Cutting near Waikato Falls	N112/309830	7.87	0.75	0.66	0.74	1043	143	50	58	82	65
5	Taupo Pumice	Top of Pukeonake Cone	N112/066824	7.41	0.82	0.59	0.51	896	220	51	85	60	100
6	Mapara Tephra	Burrows Quarry basal 15 cm lapilli	N94/647394	7.55	0.90	0.87	0.30	633	106	33	41	71	39
7	Whakaipo Tephra	Mapara Road basal 15 cm pumice blocks	N94/466364	8.45	0.50	0.70	0.35	443	73	35	24	454	61
8	Waimihia Lapilli	Napier-Taupo Highway basal 20 cm pumice blocks	N94/572354	7.28	1.23	0.79	0.67	699	149	24	27	332	41
9	Waimihia Lapilli	Wairakei-Putaruru Highway (Route 1)	N94/516544	8.02	0.78	0.89	0.46	1023	135	55	68	380	60
10	Waimihia Lapilli	Ohakune Mountain Road	N121/996602	9.17	0.72	0.55	0.06	1008	201	43	75	226	99
11	Waimihia Ash	Rangipo Desert	N122/165595	7.61	0.62	0.63	0.17	709	128	30	36	222	42
12	Waimihia Ash	West Taupo Road	N102/179194	7.34	0.68	0.69	0.16	714	95	40	38	239	98
13	Waimihia Ash	Desert Road	N122/219675	10.44	1.29	0.77	0.25	989	136	50	87	225	126
14	Hinemaiaia Ash	*P28856	N94/587347	8.08	0.55	0.82	0.29	887	85	44	55	663	50
15	Hinemaiaia Ash	National Park-Taupo Road	N112/125924	6.55	0.59	0.65	0.08	762	99	34	35	176	80
16	Opepe Tephra	Napier-Taupo Highway	N94/572354	7.24	0.80	0.59	0.37	3470	117	69	87	226	59
17	Poronui Tephra	P28866	N94/587347	7.81	0.76	0.61	0.18	3066	114	75	99	280	56
18	Poronui Tephra	Iwatahi Gully basal 15 cm lapilli & ash	N103/735200	7.02	0.67	0.47	0.24	3602	131	75	110	136	78

Analysis No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
19	Poronui Tephra	Desert Road	N112/298951	6.25	0.90	0.52	0.23	2804	113	82	99	497	59
20	Poronui Tephra	Above Taupo-Turangi Road	N102/341070	6.10	0.72	0.53	0.13	2960	102	76	90	584	107
21	Poronui Tephra	Head of Waipakihi River	N112/431846	8.78	0.75	0.38	0.08	3039	146	66	113	193	74
22	Papanetu Tephra	Top of Kuharua Dome	N102/188032	7.34	1.09	0.37	0.10	3531	710	127	179	114	72
23	Papanetu Tephra	Te Ponanga Road	N112/224983	6.91	0.90	0.50	0.09	3889	285	101	163	284	133
24	Papanetu Tephra	Te Ponanga Road	N102/256015	6.30	1.10	0.43	0.08	4044	462	113	179	217	107
25	Karapiti Lapilli	Iwatahi Gully basal 5 cm lapilli & ash	N103/735200	6.92	0.87	0.54	0.10	3906	179	75	115	192	64
26	Karapiti Lapilli	P28865	N94/587347	7.43	0.67	0.57	0.14	3090	111	76	114	350	50
27	Rotorua Ash	Rotorua-Taupo Highway basal 15 cm lapilli & ash	N76/780908	4.21	0.98	0.59	0.63	2039	124	48	56	524	20
28	Rotorua Ash	Lynmore Hill 20 cm from top - ash	N76/774010	4.99	0.93	0.62	0.06	2364	161	75	67	639	22
29	Rotorua Ash	Road west side Lake Rotorua, basal pumice blocks	N76/677135	5.29	0.92	0.64	0.41	2398	143	48	43	453	43
30	?Rotorua Ash	Cutting near Waikato Falls	N112/301844	4.69	1.04	0.51	0.07	3178	492	82	150	394	36
31	?Rotorua Ash	Mangatepopo Track	N112/069798	4.99	1.01	0.59	0.18	2633	532	84	119	270	52
32	?Rotorua Ash	Otamangakau Canal	N112/105979	5.79	0.98	0.63	0.10	2968	454	94	155	337	112
33	Puketerata Ash	Wairakei-Putaruru Highway (Route 1)	N94/516544	6.39	0.43	0.78	0.50	1936	179	82	79	435	56
34	?Puketerata Ash	Desert Road	N112/250806	5.39	0.66	0.71	0.13	1923	141	60	66	409	83
35	Rerewhakaaitu Ash	Democrat Road basal 15 cm ash	N86/934824	4.79	0.61	0.71	0.11	2122	149	58	67	733	41
36	Rerewhakaaitu Ash	Gavin Road	N86/995824	5.34	0.45	0.62	0.24	1920	151	35	33	684	20
37	Rerewhakaaitu Ash	Mangatepopo Valley (on moraine)	N112/089823	5.06	0.54	0.70	0.09	2245	142	53	46	451	34
38	?Rerewhakaaitu Ash (contaminated)	National Park-Taupo Road	N112/239901	6.67	0.73	0.62	0.10	3389	351	80	103	602	76
39	Oruanui Ash	Wairakei-Putaruru Highway (Route 1) basal lapilli	N94/523521	6.17	0.62	0.44	0.16	2714	195	75	69	184	36
40	Oruanui Ash	Braemar Road 12 cm from top	N68/202265	5.30	0.80	0.55	0.11	2963	261	90	115	391	95
41	Oruanui Ash	Rangipo Desert	N122/175575	6.47	1.01	0.51	0.30	3292	250	85	109	223	70
42	Oruanui Breccia	NE side Tongariro River	N102/303015	5.78	0.75	0.63	0.86	3559	239	72	100	418	63

DESCRIPTIONS OF RHYOLITIC TEPHRAS

Taupo Pumice (tp)

Taupo Pumice has long been recognised as an important and widespread deposit in the study area and was once believed to have been erupted from the Tongariro volcanoes (Dieffenbach 1843, p. 128; Wakefield 1845, p. 236; Taylor 1855, p. 225). Gregg (1960, p. 39) summarised previous work and showed its distribution by a generalised isopach map. However, within the Tongariro area varying amounts of primary deposits (airfall and nuée ardente origin, almost certainly erupted from more than one source) and water-sorted pumice make the distribution pattern more complex.

In the northern part of the area two further members of the Taupo Pumice Formation are present. Rotongaio Ash (Baumgart 1954; Healy 1964) with its distinctive steel-grey colour is 5.20 mm thick at sections near Kuratau (Fig 1) and also about 20 mm thick on Kepa Road, east of Turangi (N102/382012). At the latter locality 20 mm of cream coloured ash ('Putty Ash', Tsg member 5; Healy 1964) underlies Rotongaio Ash but has not been seen further south.

According to Gregg (1960) the Taupo Pumice defines the top of the Mangatawai Ash and the base of the Ngauruhoe Ash.

Whakaipo Tephra (wo)

Whakaipo Tephra (Vucetich and Pullar 1973) can be identified in the northern part of the region studied where it is of lapilli grade. On Kepa Road (N102/382012) 90 mm of pale yellow Whakaipo Tephra occurs within Mangatawai Ash 0.16 m above Waimihia Lapilli. Further south, the Mangatawai Ash separating them becomes indistinct so that Whakaipo Tephra cannot be distinguished from Waimihia Lapilli. Still further south (N122/223671) Whakaipo Tephra is significantly finer.

Correlation was established by stratigraphy and presence of hypersthene + augite. Titanomagnetite was not analysed.

Waimihia Lapilli (wm)

Waimihia Lapilli (Baumgart 1954; Healy 1964) can be identified up to 9 km south-west of Ruapehu (N121/993595) and in the southern area of the Rangipo Desert (N122/165595; 10 km southeast of Ruapehu). It has not been found to the west of the volcanoes.

In the south (N122/097565) the ash is fine and yellow to pale yellow and forms a well defined horizon up to 50 mm thick. About 34 km further northeast, where Waimihia Lapilli is of less use as a marker, it consists of 0.3 m of medium pale pumiceous ash scattered throughout fine yellowish brown ash.

The ferromagnesian assemblage - hypersthene + augite - and the relatively high titanium, chromium and zirconium, and low vanadium, cobalt and nickel of the titanomagnetites confirms identification as Waimihia Lapilli (Table 4 analyses 8-13). It is distinguished from the otherwise mineralogically and chemically similar Taupo Pumice by its relatively high zirconium content (>100 ppm).

Hinemaiaia Ash (hn)

Fine white rhyolitic tephra interbedded with the Papakai Tephra (Table 1) and occurring at all sections along the Desert Road from Makahikatoa Stream bridge (N112/250787) south to Mangatoetoenui Stream (N112/216709) is correlated with Hinemaiaia Ash (Vucetich and Pullar 1973). Between these localities the ash typically occurs about 0.15 m above Poutu Lapilli and about 0.5 m below the top of Papakai Tephra (Topping 1973). Near Makahikatoa Stream, Hinemaiaia Ash occurs as "cream cakes" (Healy 1964, p. 10) or in isolated pockets. Further south, and due east of the Tama Lakes, it forms a continuous horizon. It is suggested that the continuous eruption of andesitic tephra from one of the Tongariro vents protected Hinemaiaia Ash from subsequent erosion or disturbance during soil-forming processes.

North of Tongariro Hinemaiaia Ash occurs in only a few sections. On an old Ketetahi Springs track (N112/135915) it is 50 mm thick and 50 mm above the base of the 0.73 m-thick Papakai Tephra. About 1.3 km WNW (N112/125924) it occurs as an isolated pocket, 60 mm thick, in the lower part of the Papakai Tephra. The occurrence of Hinemaiaia Ash to the north of Tongariro in pockets only rather than a continuous horizon indicates little protection from erosion by subsequent andesitic tephras.

According to the stratigraphic position and ferromagnesian mineral content - hypersthene + augite - the ash could be Hinemaiaia Ash or Opepe Tephra. However, the titanomagnetite analysis (Table 4, analysis 15) identifies the ash as Hinemaiaia Ash.

?Rotoma Ash (rm)

The rhyolitic ash scattered through 20 mm of peat in the swamp cut by the Otamangakau Canal (N112/109984) has an age, by interpolation, of 7,430 yrs B.P. According to Pullar and Heine (1971) Rotoma Ash has an age of 7,330±235 yrs B.P. (N.Z. 1199). The ferromagnesian assemblage of a sample from the peat comprises hypersthene + biotite + calcic-hornblende + augite. That for the Rotoma Ash (Vucetich and Pullar 1964) comprises calcic hornblende + hypersthene + rare augite. The amount of biotite in the sample from the swamp is anomalously high. Most of the augite in the sample from the peat is larger in size than the other ferromagnesian minerals and is probably contamination from andesitic tephras. The age, and presence of calcic-hornblende suggests correlation with Rotoma Ash.

Opepe Tephra (op)

Opepe Tephra (Vucetich and Pullar 1973) is only recognised in a peat swamp cut by the Otamangakau Canal (N112/109984). The estimated age from the uniform rate of peat accumulation is 8,600 yrs B.P. which compares well with a radiocarbon age of 8,850±1000 yrs B.P. (Healy 1964). The deposition of Opepe Tephra occurred at the time of maximum soil development on Papakai Tephra making its preservation outside of peat swamps very unlikely.

Poronui Tephra (po)

Poronui Tephra (Vucetich and Pullar 1973) is a rhyolitic tephra erupted from Taupo Volcanic Centre. North of Tongariro, Poronui Tephra is enclosed by Poutu Lapilli and Te Rato Lapilli, but to the east Te Rato Lapilli is thin or absent.

Poronui Tephra is typically exposed in the Poutu Canal - eastern National Park-Taupo Road region where it comprises fine yellow ash 10-30 mm thick. It is also present at reference sections: Poutu (Fig 2), Access 10, and Te Ponanga Saddle (Fig 3) and extends southwards over half the length of the Desert Road but does not occur to the west of Tongariro. It thickens northwards to 60 mm on Kepa Road (N102/382012) and eastwards to 80 mm at the head of the Waipakihi Valley (N112/431846).

A ^{14}C age of 9,780±170 yrs B.P. for Te Rato Lapilli (N.Z. 1372; Table 2) together with an estimated age of 9,700 yrs B.P. for Poutu Lapilli dates Poronui Tephra at about 9,740 yrs B.P. The preservation of Poronui Tephra as a discrete horizon is attributed to the rapid deposition of overlying andesitic beds.

The ash has been traced northwards and correlated with Poronui Tephra of the Taupo Subgroup. The ferromagnesian assemblage - hypersthene + augite - confirms this correlation. Titanomagnetite analyses of Poronui Tephra at the Iwatahi reference section (N103/735200; <u>see</u> Fig 1) and one other site (analyses 17, 18) correlate with the rhyolitic ash bracketed by Poutu Lapilli and Te Rato Lapilli at three sites in the Tongariro region (analyses 19-21). At the Iwatahi reference section Poutu Lapilli has been identified (Table 17 p.) in the paleosol of Poronui Tephra which is in turn underlain by the grey-green Te Rato Lapilli.

Papanetu Tephra (pa)

Papanetu Tephra is a new formation name for rhyolitic

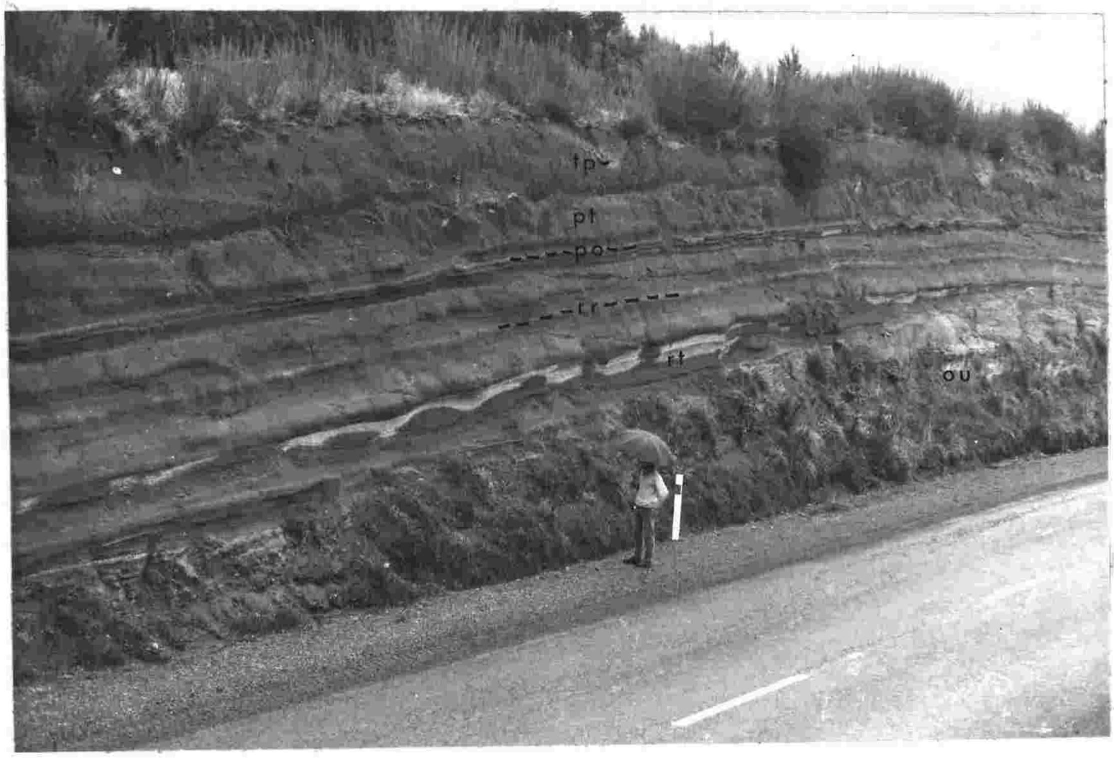

Fig. 2. - Poutu reference section on National Park - Taupo Road (N112/239901), showing four rhyolitic tephras: Taupo Pumice (tp), Poronui Tephra (po), ?Rotorua Ash (rr), Oruanui Formation (ou), and two andesitic marker beds: Poutu Lapilli (pt) and Rotoaira Lapilli (rt).

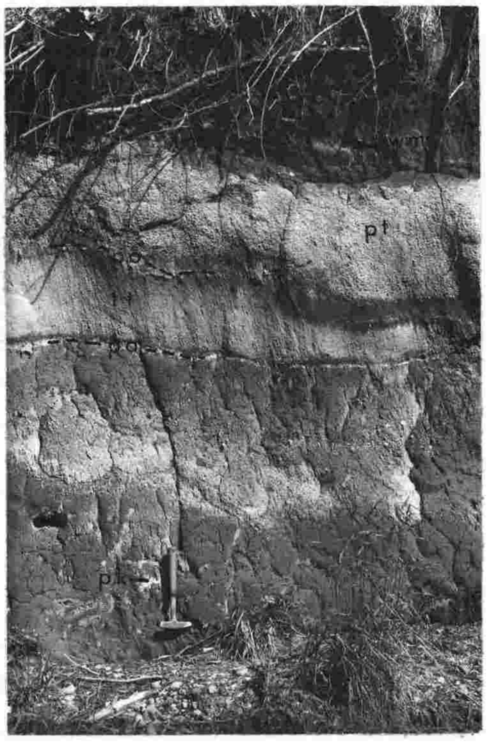

Fig. 3. - Te Ponanga Saddle reference section, Te Ponanga Saddle Road (N112/224983), type section for Papanetu Tephra. Rhyolitic tephras are: Waimihia Lapilli (wm), Poronui Tephra (po), Papanetu Tephra (pa), ?Puketarata Ash (pk), and the andesitic units are: Poutu Lapilli (pt) and Te Rato Lapilli (tt).

tephra immediately underlying the Te Rato Lapilli. At the type section on the Te Ponanga Saddle Road (N112/224983), Papanetu Tephra comprises up to 20 mm pale yellow ash with abundant grey lithic fragments and clear obsidian up to 10 mm. On Kuhurua Dome (N102/188082) Papanetu Tephra, below Te Rato Lapilli and above rhyolitic breccia, comprises 0.62 m of rhyolitic ash and coarse obsidian fragments.

The tephra is best displayed in sections along Te Ponanga Saddle Road where it is commonly 10-20 mm thick but with a range of 2-40 mm. The isopach pattern (Fig 4) and the coarse obsidian fragments indicate that the source is Kuhurua Dome.

Papanetu Tephra is bracketed by two new radiocarbon dates. Twigs from 5 mm of peat above Papanetu Tephra gave an age of 9,780±170 yrs B.P. (N.Z. 1372, Table 2), the peat gave an age of 9,700±210 yrs B.P. (N.Z. 1373, Table 2), and twigs from 20 mm of peat immediately underlying the tephra gave an age of 9,790±160 yrs B.P. (N.Z. 1374, Table 2). The age of Papanetu Tephra is taken as being 9,785 yrs B.P. and the date provides a minimum age for Kuhurua Dome.

Papanetu Tephra has a ferromagnesian assemblage comprising hypersthene + augite. Three titanomagnetite analyses, including one from the section on Kuhurua Dome, are similar except that chromium is higher in the sample from the dome (Table 4).

Karapiti Lapilli (kp)

Rhyolitic tephra correlated with Karapiti Lapilli (Vucetich and Pullar 1973) underlies Te Rato Lapilli on Kepa Road and at sections further north. Karapiti Lapilli and Papanetu Tephra both directly underlie Te Rato Lapilli without evidence of significant time break. The age of Karapiti Tephra is therefore considered to be about 9,785 yrs old.

Two titanomagnetite samples of Karapiti Lapilli were analysed (analyses 25, 26; Table 4) and found to be significantly lower in chromium, cobalt and nickel than Papanetu Tephra samples. Karapiti Lapilli and Papanetu Tephra both have a hypersthene + augite ferromagnesian assemblage so cannot be distinguished on mineralogy.

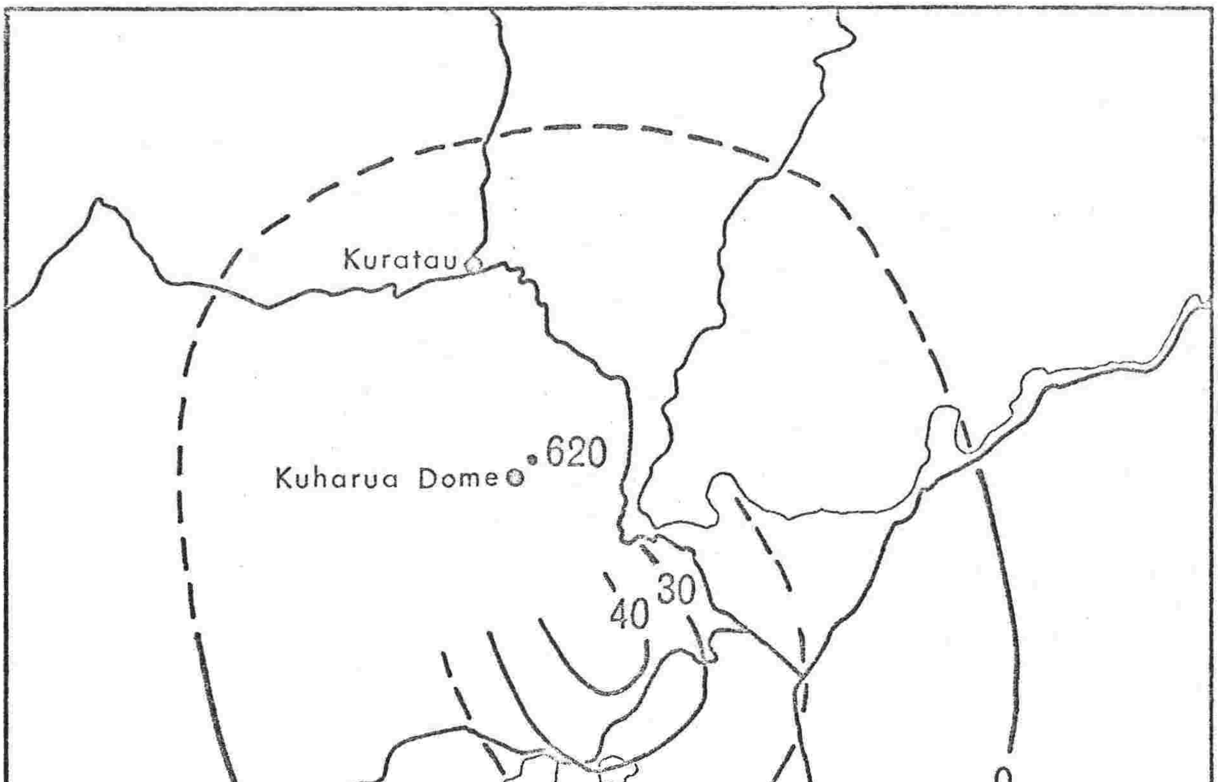

Fig. 4. - Isopach map of Papanetu Tephra (based on 77 measurements). All thicknesses are in mm.

?Rotorua Ash (rr)

A fine yellow rhyolitic ash that probably correlates with Rotorua Ash (Vucetich and Pullar 1964) occurs about midway between Te Rato Lapilli and Rotoaira Lapilli in sections to the north of Tongariro, and in about half of all sections elsewhere in the study area spanning this time range. The ash extends as far westwards as Moerangi and south almost to Waiouru (Fig 1) and reaches a maximum thickness of 60 mm. It occurs typically as small "cream cakes" (Healy 1964, p. 10) or in small pockets to the north of Tongariro (e.g. at reference sections: Poutu, Access 10, and Mangatawai, see also Fig 5 and appendix). At sections on the National Park -Taupo Road south of Taurewa it occurs as a discrete horizon where overlain by tephra from Mt. Ruapehu.

Its wide distribution and its fine grain size suggests a distant source. Two dated andesitic tephras (12,350±220 yrs B.P., N.Z. 1187; 13,150±300 yrs B.P., N.Z. 1186; Table 2) from a section at N112/105987 can be correlated with a section 0.5 km to the northwest (N112/102990) where they bracket the rhyolitic ash and indicate an age of about 12,500 yrs B.P. The ferromagnesian assemblage comprising hypersthene + calcic-hornblende + biotite + augite suggests correlation with a Rotorua Subgroup tephra and the Rotorua Ash with an estimated age of 13,000 yrs B.P. (Vucetich and Pullar 1964) is a probable correlative.

Three titanomagnetite analyses (analyses 30-32, Table 4) from the Tongariro region contain significantly higher vanadium, chromium, cobalt and nickel than three near-source Rotorua Ash samples (analyses 27-29). However, the presence of some very large augite and hypersthene in the Tongariro samples may indicate contamination by andesitic tephra which is known to contain greater amounts of these four elements than does Rotorua Ash.

This tephra constitutes the most valuable time plane in the Tongariro area.

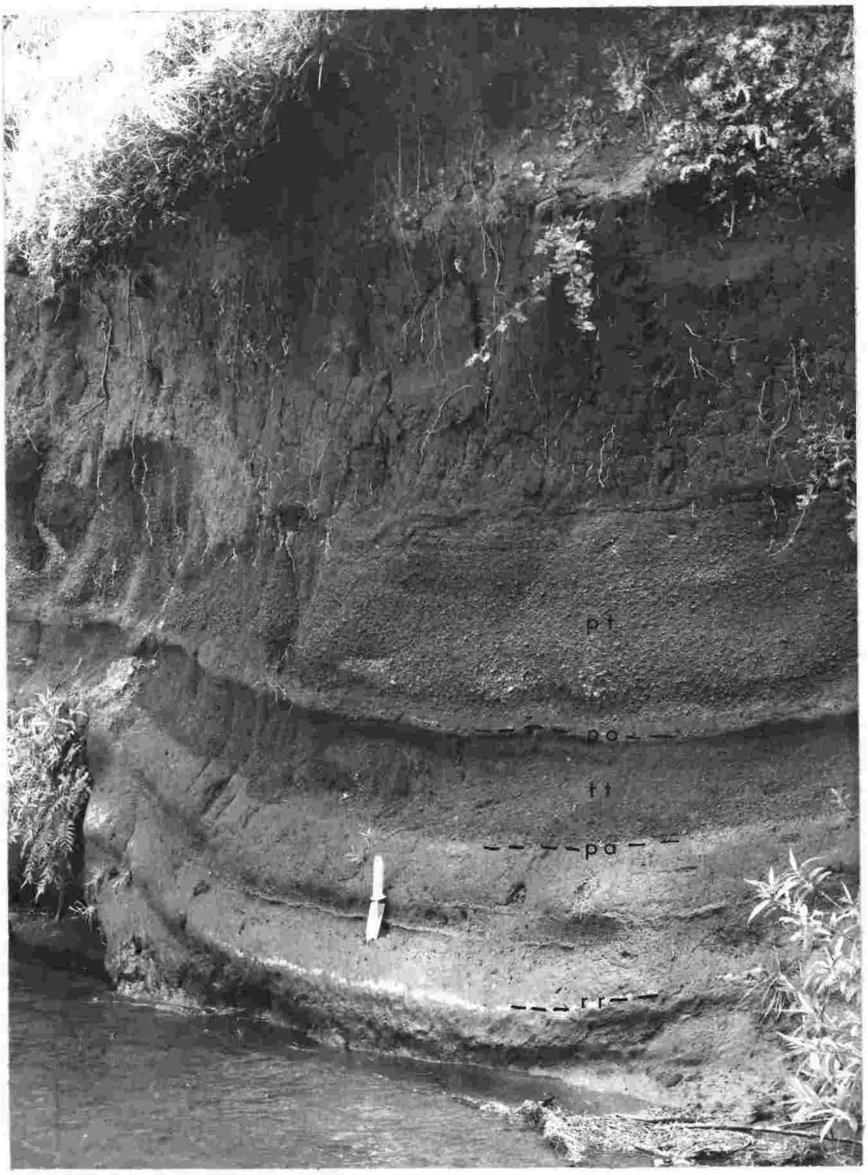

Fig. 5. - Tephra section on eastern side, Motuopuhi Island, Lake Rotoaira (N112/198956), showing the rhyolitic ?Rotorua Ash (rr), Papanetu Tephra (pa), Poronui Tephra (po), and the andesitic Poutu Lapilli (pt) and Te Rato Lapilli (tt). The trowel is 0.29 mm in length.

?Puketarata Ash (pk)

At the Mangatawai reference section (N112/250806) a rhyolitic tephra comprising a calcic-hornblende + hypersthene + minor biotite ferromagnesian assemblage occurs in a lens 0.19 m thick and 1.46 m long, 0.53 below ?Rotorua Ash, and above Rotoaira Lapilli (Topping 1973). The stratigraphic position, ferromagnesian assemblage and titanomagnetite composition (analyses 33, 34) identify the tephra as Puketarata Ash.

At a section near Wairehu Canal (N112/145983) a rhyolitic tephra containing a biotite + hypersthene + minor calcic-hornblende and augite ferromagnesian assemblage, occurring between ?Rotorua Ash and Rotoaira Lapilli is also considered to be Puketarata Ash. Rerewhakaaitu Ash (see below) has been correlated with a tephra occurring below Rotoaira Lapilli at the Te Ponanga Saddle reference section so that the correlation with Puketarata Ash is supported by a section at Palmer Road (N94/542499) where Puketarata Ash is bracketed by Rotorua and Rerewhakaaitu Ashes (see p. 104).

Isopachs for Puketarata Ash (Lloyd 1972) show traces of the ash at Wairakei but a consideration of the exponential fallout pattern of tephra suggests that it may have been deposited as far south as Tongariro.

Rerewhakaaitu Ash (rk)

A 40 mm lens of white to pale yellow fine rhyolitic ash occurs within andesitic tephras 1 m below ?Rotorua Ash in a section on the lateral moraine on the northern side of Mangatepopo Valley (N112/089822). The ash is correlated with Rerewhakaaitu Ash (Vucetich and Pullar 1964), erupted from the Okataina Volcanic Centre about 14,700±200 yrs B.P. (N.Z. 716).

Rerewhakaaitu Ash is considered to be present as the rhyolitic tephra below Rotoaira Lapilli and above Oruanui Ash at the Te Ponanga Saddle reference section and 0.15 m below Rotoaira Lapilli at the Poutu reference section.

The ferromagnesian mineral assemblage contains biotite + hypersthene + calcic-hornblende ± augite. Rerewhakaaitu Ash samples from near source have a similar ferromagnesian assemblage but are not known to contain augite (Cole 1970). Titanomagnetite analysis of the ash (without augite) on the moraine in Mangatepopo Valley agrees well with known Rerewhakaaitu Ash samples (analyses 35-38).

Oruanui Formation (ou)

The Oruanui Formation occurs throughout the whole region and its distribution is consistent with an interpolation of Vucetich and Pullar's (1969, p. 798) isopach map. The two members - Oruanui Breccia (tephra-flow) and underlying Oruanui Ash (tephra-fall) - have been radiocarbon dated at 20,600±300 yrs B.P. (N.Z. 12, Vucetich and Pullar 1969).

The Oruanui Breccia consists of pale brownish grey massive ash and rare lapilli and is typically seen on the Rotoaira Road (N112/176979), where the upper 2.7 m is clearly exposed. The contact between the two members is best seen at the Poutu reference section (N112/239901). At a more westerly section (N112/125924) a lens of andesitic boulders and cobbles separate two possible flow units. The possibility of more than one flow unit within Oruanui Breccia could also be explained by slumping after a period of erosion.

The Oruanui Ash is a distinctive air-fall unit containing chalazoidites (Vucetich and Pullar 1969). North of Tongariro, the shower-bedded base of the ash either overlies sands and gravels or a very dark brown tuff containing plant fragments.

The two Oruanui members do not occur above an altitude of 1200 m. On the western slopes of Tongariro up to an altitude of 1,070 m Oruanui tephra forms the matrix of alluvial deposits and is interbedded with gravels at a section 13 km SE of Mt Ruapehu (N122/175575). Reworked Oruanui tephra occurs at 1,100 m at the head of the Waipakihi Valley (N112/431846) and is 2.4 m thick further down valley at a height of 1,000 m (N112/377795). The ash occurs up to 670 m altitude on Te Ponanga Saddle Road (N102/238004) while Oruanui Breccia is absent above 580 m (N102/244009) in the same area.

The ferromagnesian assemblages of Oruanui samples in the study area comprise hypersthene + augite + calcic-hornblende which is the same as that for Oruanui tephra in the type area. Titanomagnetite analyses from Oruanui Breccia and Ash (analyses 41, 42) compare well with known samples in the Taupo and Rotorua districts (analyses 39, 40).

REWORKED TEPHRA DEPOSITS

Hinuera Formation

Water-laid pumiceous silts, sands and gravels are exposed in several sections to the north of Tongariro and vary from large scale current-bedding (as at Poutu reference section) to smaller cross-bedding (as at a section east of Pihanga, N112/298951). It is probably reworked Oruanui Formation and is considered to correlate with Hinuera Formation (Healy 1946; Thompson 1958; Grindley 1959; Schofield 1965; Vucetich and Pullar 1969; Lloyd 1972).

In all instances Hinuera Formation within Tongariro area overlies Oruanui Formation and is in turn overlain by Rotoaira Lapilli (Topping 1973). It is therefore younger than 20,600 yrs B.P. and older than 13,800 yrs B.P. (the maximum age of Rotoaira Lapilli; Table 2) and can be correlated with Hinuera-2 sediments (Schofield 1965).

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APPENDIX IV

IDENTIFICATION OF LATE QUATERNARY TEPHRAS FOR DATING TARANAKI LAHAR DEPOSITS.

Submitted to the N.Z. Journal of Geology and Geophysics.
The paper is given here in manuscript form.

IDENTIFICATION OF LATE QUATERNARY TEPHRAS FOR DATING TARANAKI LAHAR DEPOSITS.

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ABSTRACT

Major and minor elements were analysed from titanomagnetites extracted from 12 Taranaki tephras. The tephras fall into five groups characterised by specific abundances of chromium, vanadium, nickel, cobalt and manganese. The titanomagnetite analyses allow the positive identification of two widespread, but thin tephras at distances >25 km from their source. The preservation and identification of these dated tephras between three extensive lahar deposits in western Taranaki allows age limits to be placed on periods of lahar deposition. The oldest lahar is dated (N.Z.942) at >16,100 yr B.P. The middle lahar deposit is dated (N.Z.1143 and N.Z.942) between 12,500 and 16,100 yr B.P. The youngest lahar is dated (N.Z.1144) at <6,970 yr B.P.

Titanomagnetite analyses from Tongariro eruptives are more basic in composition than those from Taranaki tephras and this regional difference allows source areas to be determined for soil parent materials in areas between the two volcanic centres.

INTRODUCTION

The recent volcanic history of Taranaki is dominated by the activity of Egmont and Pouakai volcanoes (Fig 1). Extensive ringplains of detrital volcaniclastics slope away from each centre. Marker beds from a 30 m tephra column on Pouakai ringplain, to the north of Mt Egmont, have been 14C dated on their content of wood, peat and charcoal (Neall 1972). This allows correlation between late Quaternary sections over 1,000 km^2. To the south, on the younger Egmont ringplain, much of the tephra has been destroyed by volcanic activity or is overlain by later lahar deposits. The positive identification of dated tephra layers on Egmont ringplain thus enables interspersed volcanic events to be accurately dated.

IDENTIFICATION OF TEPHRAS

General

With increasing distance from source tephra marker beds thin out and change in lithology and appearance so that at distances greater than 25 km only tentative correlations can be made. Identification by laboratory methods is therefore critical in tracing Taranaki tephras into peripheral Quaternary sequences, to extend the range of present time control.

Initial investigations by the authors attempted to identify known Taranaki tephra layers by physical and optical methods, but with little success. Most

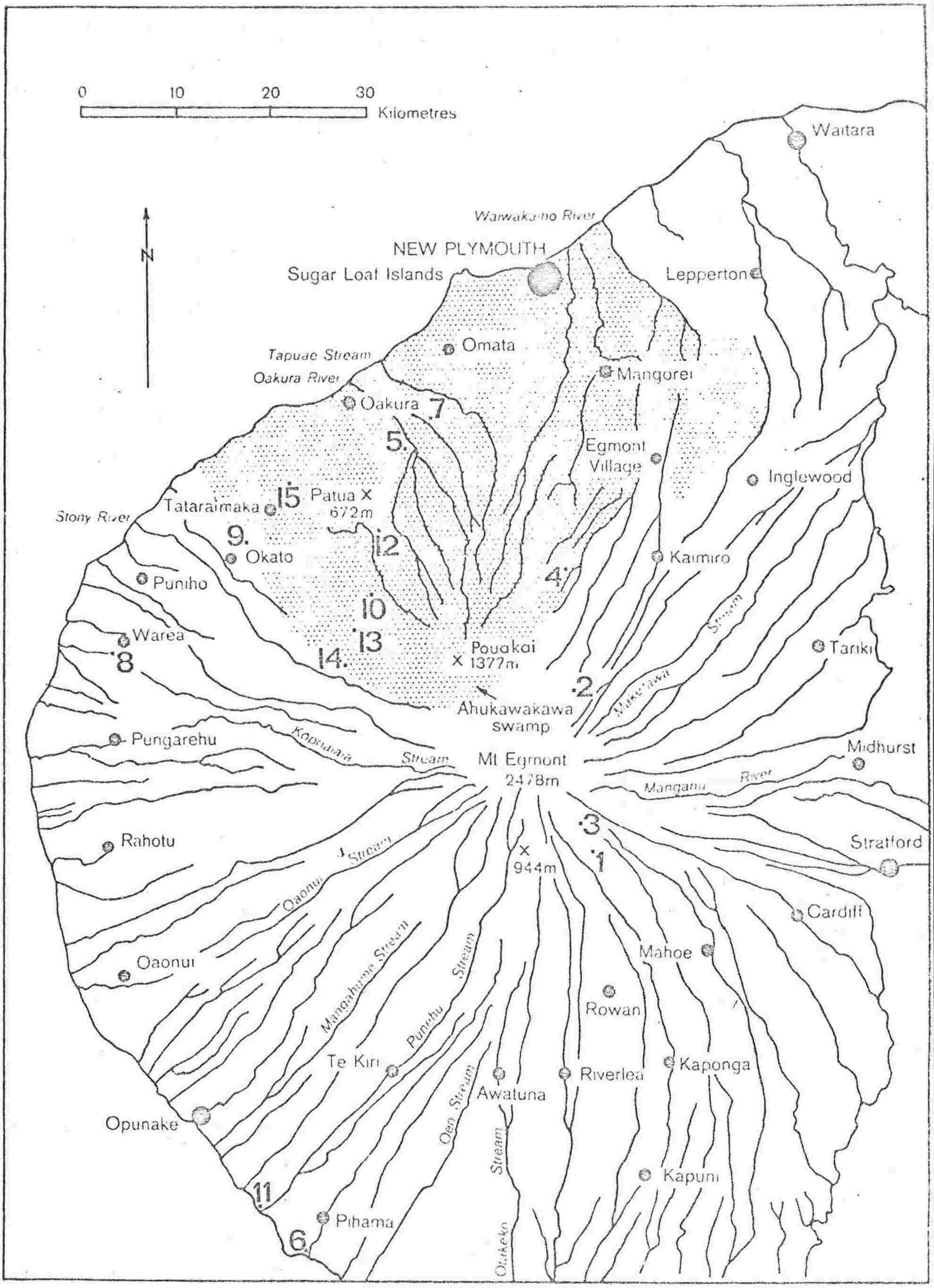


Fig. 1. - Locality map of Taranaki, showing sample sites. Numbers refer to localities in Table 2. Dotted area outlines surfaces graded to Pouakai volcano.

methods for identifying tephras require distinctive properties of volcanic glasses or phenocrysts. Glass and plagioclase weather rapidly to allophane under Taranaki climatic conditions and are only fresh in the youngest eruptives. Allophane is the dominant clay mineral in the younger tephras, and halloysite is restricted to the uppermost New Plymouth Buried Soil and buried soils beneath (Table 1), where it coexists with allophane. The presence of halloysite is therefore of limited use for tephra correlation. Although the age of the allophane-halloysite transition in Taranaki is not accurately dated, extrapolated tephra accumulation rates suggest it is between 70 - 100,000 yrs B.P. This is in marked contrast to the age of the major transition in the Rotorua-Bay of Plenty region which is dated at 20,000 yrs B.P. (Mr C.G. Vucetich, pers.comm.).

Ferromagnesian phenocryst assemblages have been used for tephra correlation in the United States, but this technique shows greatest potential with rhyolitic and dacitic tephras and also where tephras are derived from different source areas (Wilcox 1965). Samples of the principal Taranaki tephras were examined for ferromagnesian phenocryst abundances. Abundant augite, titanomagnetite and rare hornblende characterise all the tephra heavy mineral assemblages. Hypersthene is absent from Weld tuff and the uppermost New Plymouth Ashes. Where present, hypersthene commonly forms distinctive acicular or equant crystals averaging 0.02 mm across in contrast to augite which averages 0.25 mm across. Seven samples from the youngest eruptives examined by Tonkin (1970), show similar mineralogy except for the absence of hypersthene in the Burrell Ash. A diagnostic feature of augite crystals within the tephras is that with increasing age they become increasingly etched. In tephras above the New Plymouth Ashes the augites show only weak

	FORMATIONS	NAMED MEMBERS	UNNAMED ASHES	SYMBOLS	AUTHOR	AGE
	TAHURANGI FORMATION	TAHURANGI ASH		Ta	Druce (1966)	1755 AD
	BURRELL FORMATION	PUNIHO LAPILLI 2		Pl 2	Druce (1966)	1655 AD
		PUNIHO LAPILLI 1		Pl 1		1655 AD
		BURRELL LAPILLI		Bl		1655 AD
		BURRELL ASH		Ba		1655 AD
	NEWALL FORMATION	WAIWERANUI ASH		Wa	Druce (1966)	Revised Age
		WAIWERANUI LAPILLI		Wl		1500 - 1550 AD
		NEWALL LAPILLI		Nl		
		NEWALL ASH		Na		
			Unnamed Ash Beds			
	INGLEWOOD TEPHRA			Il		
	KORITO TEPHRA			J		
EGMONT SHOWER	OAKURA TEPHRA		Unnamed Ash	Eg 1	Grange and Taylor 1931, 1933	<6,970 ± 76 Yrs. B. P.
		Basal lapilli	Eg 1 lap.			
	STENT ASH				Wellman (1962)	
	OKATO TEPHRA		Unnamed ash 2A Unnamed lapilli Unnamed ash 2B	Eg 2	Grange and Taylor 1931, 1933	
		Ahuahu Lapilli	Aa			
	SAUNDERS ASH			Gg		16,100 ± 220 yrs.
	CARRINGTON TEPHRAS			Ct		
	KORU TEPHRA	Koru ash		Ka		
		Koru lapilli		Kp		
	——— ———	——— ———	———	———	———	———
	PUKEITI TEPHRA			Pk		
	WELD TEPHRA	Weld ash		Wd		
		Weld tuff		Wt		
	——— ———	——— ———	———	———	———	———
			Unnamed Ash Unnamed Lapilli			
	NEW PLYMOUTH ASHES AND BURIED SOILS			NPA NPBS		

Table 2. - Stratigraphic column of Taranaki tephras (modified after Neall 1972).

etching on basal pinacoid faces (Fig.2A), but below this horizon moderate to severe etching occurs on the basal pinacoid (Fig.2B) and the crystal faces of some pyroxenes are completely destroyed by corrosion.

Bulk chemical analyses are considered unsatisfactory for correlation purposes because of the rapid weathering of glass and varying amounts of phenocrysts within the Taranaki tephra deposits.

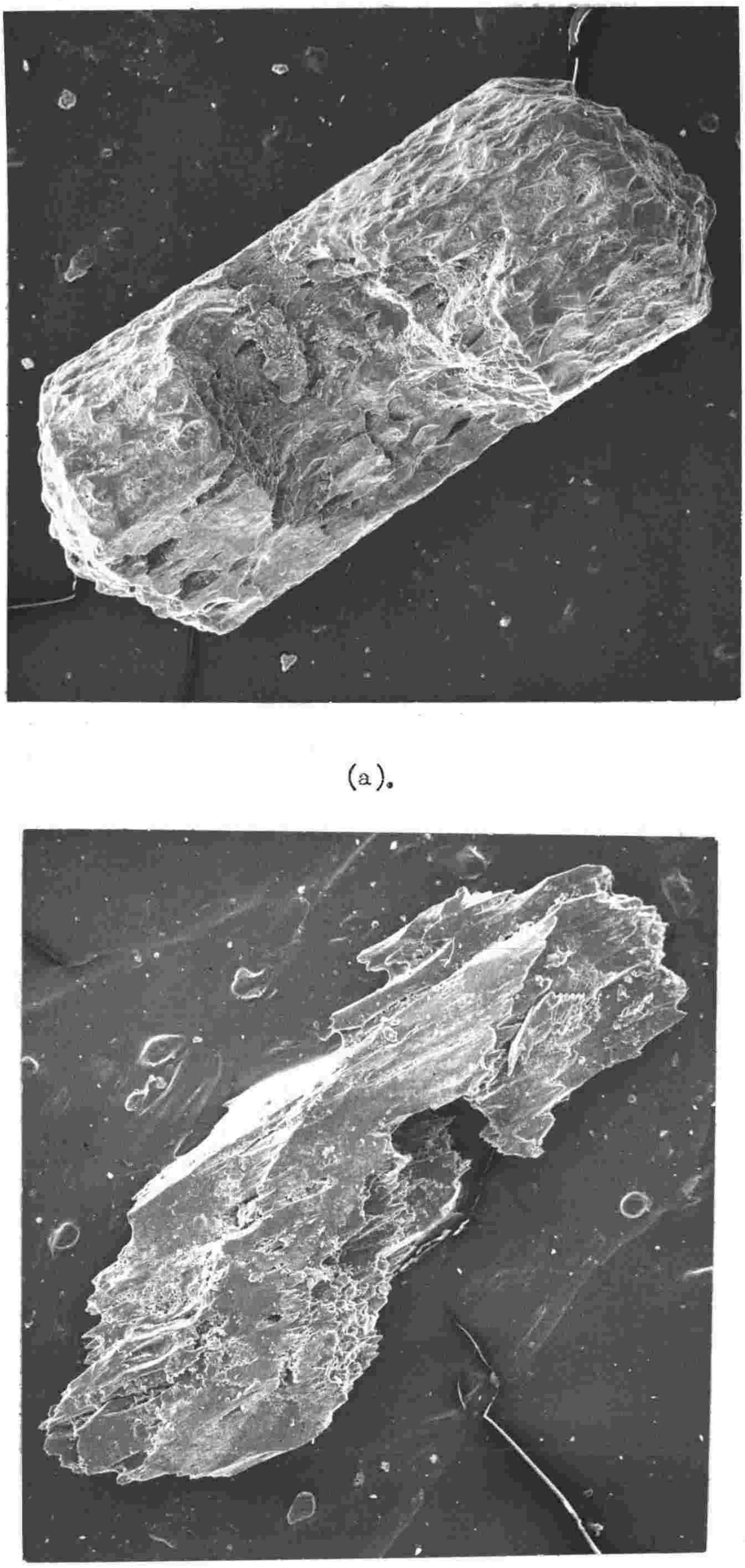
Identification by Titanomagnetite Analyses

A method for the identification of tephras involving recognition of chemical variations within titanomagnetite, analysed by optical emission spectroscopy, has been described by Kohn (1970). The method is particularly suitable for use in the Taranaki area where all tephras contain abundant titanomagnetite, a mineral which has been shown by Aomine and Wada (1962) and Ruxton (1968) to be relatively stable during weathering. To assess the potential of the technique for identifying Taranaki tephras mostly derived from a similar source, 31 samples of titanomagnetite from 15 localities (Fig.1) were separated.

Results of analyses from 12 Taranaki tephras are presented in Table 2. The tephras fall into five groups (a - e), based on similarity of elemental abundances.

a) Burrell Lapilli, Waiweranui Ash, Newall Ash, Oakura Tephra, Ahuahu Lapilli member of Okato Tephra, Saunders Ash and Weld tuff.

b) Okato Tephra (above Ahuahu Lapilli member)



(a).

(b).

<u>Fig. 2.</u> - Scanning electron microscope photographs of:

(a). Weakly etched augite crystal, note cavity on side previously occupied by titanomagnetite crystal, x 180.

(b). Moderately to severly etched augite crystal x 200.

and Koru Tephra.

c) Inglewood Tephra.

d) Pukeiti Tephra.

e) New Plymouth Ashes.

Chromium is the most variable element between these groups, a finding similar to that of Duncan and Taylor (1968) for titanomagnetites from andesitic and and dacitic lavas from Bay of Plenty. Vanadium, cobalt and nickel values are generally similar in groups (a), (b) and (e) but are less abundant in Inglewood Tephra and Pukeiti Tephra. Manganese abundances in titanomagnetites from Inglewood Tephra and Pukeiti Tephra are markedly higher than those in other groups. Values obtained from the upper ash and basal lapilli of the Oakura Tephra at Hurford Road (Table 2) show similar composition and thus indicate no differential weathering and suggest deposition during one volcanic event.

There are no systematic differences in titanomagnetite composition with time from tephras above the New Plymouth Ashes. The markedly high chromium and nickel values in the New Plymouth Ashes indicate that these were probably erupted from a magma of different composition from that which gave rise to the younger Mt Egmont tephras. The New Plymouth Ashes are separated from the younger Egmont tephras by a widespread paraconformity and are only preserved on the older Pouakai ringplain. From this evidence together with the titanomagnetite analyses it is suggested that these tephras were erupted from the older Pouakai Volcano; the magma differing slightly in composition to that from Egmont. Titanomagnetite from tephras and lavas in the Tongariro-National Park region also show increasing chromium and nickel values relative to younger samples indicating a similar change in both regions with time.

Locality No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
1	Burrell Lapilli	Dawson Falls	N119/682593	4.16	1.67	0.40	1.03	3662	131	188	159	57	182
1	Burrell Lapilli (lithic fragments)	Dawson Falls	N119/682593	4.84	1.11	0.44	0.76	4075	112	164	171	112	247
2	Burrell Ash	Translator Road	N119/668647	4.88	1.20	0.49	0.48	3528	95	157	134	67	178
2	Waiweranui Ash	Translator Road	N119/668647	5.41	1.22	0.64	0.28	3220	106	147	117	93	146
2	Newall Ash	Translator Road	N119/668647	5.13	1.32	0.51	0.85	3484	71	156	136	103	217
3	Newall Ash (above maori oven)	Mt Egmont	N119/678607	4.78	1.34	0.51	0.80	3387	102	149	118	110	171
2	Unnamed ash (beneath Newall Ash)	Translator Road	N119/668647	5.31	1.21	0.54	0.27	3300	99	147	111	73	135
4	Inglewood Tephra	Maude Road	N109/672751	4.09	1.30	0.74	1.22	3008	164	109	94	57	142
5	Oakura Tephra	Plymouth Road	N108/584818	5.46	1.82	0.49	0.16	4122	94	185	153	85	148
6	Oakura Tephra	Puketapu Road	N128/509357	5.01	1.70	0.59	0.40	3914	110	170	130	85	141
7	Oakura Tephra	Hurford Road	N108/592843	5.85	1.96	0.51	0.16	4521	114	185	156	79	117
8	Oakura Tephra	Warea	N108/410703	5.63	1.91	0.55	0.12	4401	87	180	141	93	201
7	Oakura Tephra (basal lapilli)	Hurford Road	N108/592843	5.07	2.01	0.52	0.47	3857	115	192	139	57	94
9	Oakura Tephra	Okato - Main Road	N108/476758	5.31	1.89	0.60	0.10	3760	93	170	122	87	114
10	Okato Tephra (upper lapilli)	Dover Road/ Carrington Road	N108/552713	4.80	1·55	0.60	0.63	3567	220	158	109	68	88
6	Okato Tephra (ash)	Puketapu Road	N128/509357	5.63	2.11	0.64	0.19	3998	187	207	139	123	116
8	Okato Tephra (ash)	Warea	N108/410703	5.61	2.03	0.62	0.12	4054	254	197	142	109	120
7	Okato Tephra	Hurford Road	N108/592843	5.17	2.09	0.59	0.10	3982	343	181	171	75	121
11	Okato Tephra (ash)	Taungatara River Mouth	N128/478394	5.29	2.06	0.64	0.12	4075	188	190	142	83	117

Locality No.	Sample	Locality	Grid Reference	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
12	Okato Tephra (Ahuahu Lapilli)	Pukeiti	N108/564742	5.23	1.98	0.55	0.34	3455	73	191	136	64	112
10	Okato Tephra (Ahuahu Lapilli)	Dover Road/ Carrington Road	N108/552713	5.47	1.44	0.58	0.44	3931	83	144	111	75	102
13	Saunders Ash	Carrington Road	N108/533704	5.53	1.53	0.55	0.63	3910	73	154	118	102	181
14	Saunders Ash	Saunders Road	N118/510698	5.91	2.07	0.59	0.66	4193	85	179	142	78	182
7	Koru Lapilli	Hurford Road	N108/592843	6.06	2.27	0.77	0.36	3991	229	158	115	63	81
12	Koru Lapilli	Pukeiti	N108/564742	5.29	1.85	0.63	0.58	3840	293	158	104	79	91
12	Pukeiti Tephra	Pukeiti	N108/564742	4.31	0.96	1.17	0.16	2829	133	93	77	208	83
7	Pukeiti Tephra	Hurford Road	N108/592843	4.55	1.07	1.12	0.18	3252	135	102	79	231	78
9	Weld Tuff	Okato - Main Road	N108/476758	5.32	1.64	0.57	0.34	4678	133	175	123	71	92
15	Weld Tuff	Timaru Road	N108/503785	4.94	1.97	0.66	0.18	4100	133	179	137	57	110
15	New Plymouth Ash	Timaru Road	N108/503785	4.42	1.95	0.58	0.07	4249	501	190	192	50	118
9	New Plymouth Ash	Okato - Main Road	N108/476758	4.43	1.80	0.63	0.07	4189	759	176	197	57	133
	ANDESITIC TEPHRAS AND LAVA FROM TONGARIRO-NATIONAL PARK.												
	Poutu Lapilli	National Park-Taupo Road	N112/239901	5.77	1.15	0.43	0.66	4954	1706	163	322	103	170
	Te Rato Lapilli	Te Ponanga Road	N112/221978	3.64	0.66	0.30	1.17	4337	960	163	284	70	121
	Rotoaira Lapilli	Rotoaira Road	N112/158980	7.41	1.80	0.35	0.27	9870	2472	219	499	108	180
	North Crater - lava	North Crater	N112/136855	8.42	1.07	0.29	0.15	8809	2470	173	280	106	110

Table 2. - Chemical analyses of titanomagnetites from Taranaki tephras and Tongariro tephras and a lava (values are in ppm unless otherwise indicated). Information on analyses as for Table 6 (Part 1).

Oakura and Okato Tephra Analyses

Particular attention was given to the analysis of titanomagnetite from the Oakura and Okato Tephras which form the most widespread and important Holocene tephras in Taranaki and are also preserved between a sequence of three principal lahar units to the west and south-west of Mt Egmont. Near their source, the strongly erosive lahar flows have destroyed the underlying tephra record, and only minimal age estimates of deposits can be determined from overlying tephras. The Oakura and Okato Tephras are best preserved between the formations at the present coastline where the lahars do not incorporate underlying materials at their base and apparently did not erode the earlier deposits. Positive identification of the tephra formations between the lahar units allows both maximum and minimum ages to be obtained for periods of lahar deposition.

Near its source, the Okato Tephra (Eg 2) comprises two lapilli units (Section 7, Fig 3 and Table 1) both overlain by ash. The basal lapilli unit is widespread and has been formally named Ahuahu Lapilli (Aa) member (Neall 1972), but the upper lapilli unit is unnamed and restricted to a few sections near Pukeiti. The two lapilli beds are not separated by weathering or erosional breaks and are therefore considered to be part of the same tephra formation. The upper limit of the formation is defined by a palaeosol at the top of the ash overlying the unnamed upper lapilli unit. Titanomagnetite was analysed from the widespread upper ash and the two lapilli units of Okato Tephra (Table 2). The upper lapilli has higher chromium values than the basal Ahuahu Lapilli (Aa), (usually greater by a factor exceeding two). The Ahuahu

Lapilli (Aa) is similar to the basal lapilli of the younger Oakura Tephra (Eg 1 lap.) and thus the basal lapilli of the Okato and Oakura Tephras are chemically indistinguishable.

At Warea, Taungatara Stream and Puketapu (Fig 1) to the west and south-west of Mt Egmont, the lapilli units (Eg 1 lap., unnamed lapilli and Aa) are absent and only ashes (correlated with the Oakura and Okato Tephras) could be sampled for titanomagnetite analysis. The low chromium values of titanomagnetite (Group a) in the uppermost tephra at Warea and at Puketapu (Table 2 and Fig 3) confirm the identification as Oakura Tephra. The higher chromium values of titanomagnetite (Group b) from tephra sampled beneath the middle lahar unit and above the oldest lahar unit at Warea and at Taungatara Stream (Fig 3) confirm correlation as Okato Tephra. At Puketapu, the higher chromium values (Group b) confirm the Okato Tephra underlies the previously identified Oakura Tephra (see above) and overlies the oldest lahar unit. At Taungatara Stream, the positive identification of the Okato Tephra beneath the middle lahar unit indicates that it must be the Oakura Tephra which forms the ashy base of the youngest lahar unit. The high chromium values of titanomagnetite in the Okato Tephra at all these localities indicates that the lower ash and lapilli of the Okato Tephra are restricted to near source.

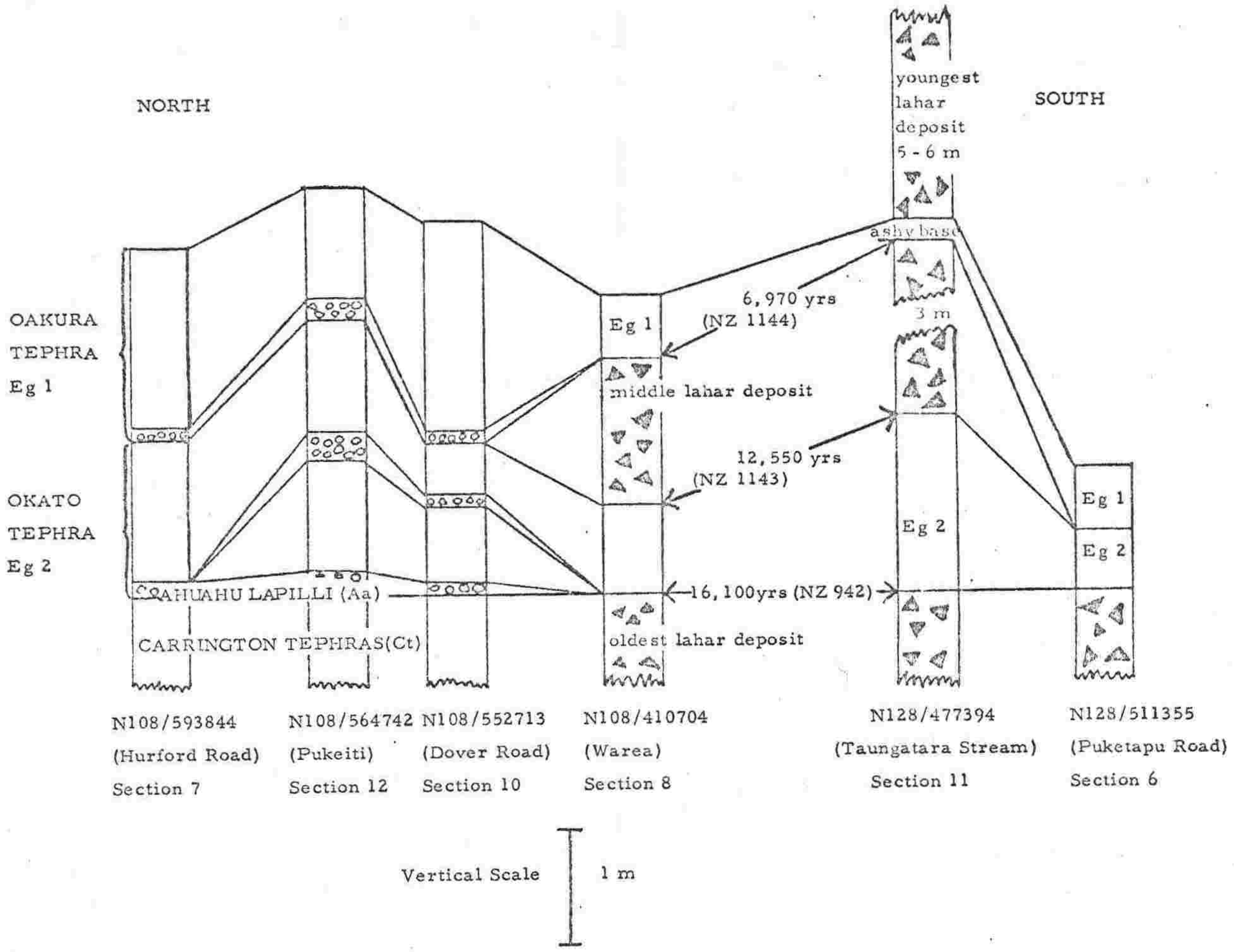


Fig. 3. - Six correlation columns between principal sample sites in western Taranaki. Section numbers refer to localities in Fig. 1 and Table 2.

CONCLUSIONS

Age of Lahar Units

The Oakura and Okato Tephras can be correlated from New Plymouth to at least as far south as Puketapu Road. Titanomagnetite analyses from these tephras, preserved between the western Taranaki lahar units at Warea, N108/410704, and at Taungatara Stream, N128/511355, confirm that beyond 25 km radius from Egmont summit:

a) the Okato Tephra overlies the oldest lahar unit and underlies the middle lahar unit,
b) the Oakura Tephra overlies the middle lahar unit and underlies the youngest lahar unit.

Since the age of the tephras has now been established in the northern part of this area (Neall 1972), the three lahar units can now be dated.

The Okato Tephra is dated (NZ1143, Grid Ref; N118/512658 and NZ942, Grid Ref; N108/534704) between 12,550 ± 150 yr B.P. and 16,100 ± 220 yr B.P., indicating a minimum age of about 16,000 years for the age of the oldest lahar unit.

The Oakura Tephra is dated (NZ1144, Grid Ref; N118/526665) at less than 6,970 ± 220 yr B.P. This indicates an age for the middle lahar unit between 7 - 14,000 yr B.P. The apparent absence of this lahar unit within a well preserved debris flow sequence near Mt Egmont, dating back to 12,550 yr B.P. (NZ1143), suggests the middle lahar originated about 13-14,000 yr B.P.

The youngest lahar unit is underlain by Oakura

Tephra, indicating an age of less than 6,970 yr B.P. (NZ1144), yet no widespread tephras mantle this lahar unit, so that it is likely to be about 3 - 5,000 yr old.

Comparison of Taranaki and Tongariro titanomagnetites

Titanomagnetite compositions of tephra from Taranaki were compared with three widespread lapilli units and a lava erupted from Tongariro Volcanic Centre (Table 2). The Tongariro eruptives contain titanomagnetite lower in manganese and higher in vanadium, nickel and chromium than the younger Taranaki eruptives. Chromium is at least three times but commonly eight times higher in the Tongariro eruptives, and is therefore the most distinctive and useful element. Thus in areas between Tongariro National Park and Mt Egmont, where late Pleistocene and Holocene tephras from the two sources may interdigitate, the andesitic tephras can be clearly distinguished on the basis of their titanomagnetite composition. Ready identification of these tephras may prove valuable in future Quaternary tephrochronology and soil genesis studies.

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APPENDIX V

Analyses of titanomagnetites from pre-44,000 yr B.P. central North Is. pyroclastic rocks. Information on analyses as for Table 6 (Part 1). Formations are not necessarily listed in stratigraphic order.

Details of sample numbers and maps for grid references as for Appendix II.

Letters preceding details of sample location refer to collectors other than the writer.

a - J.W. Cole.
b - I.A. Nairn.
c - N.D. Briggs.
d - J. Dow.

Sample No. 11937 = Ben Lomond Obsidian and was sampled at N93/429499.

<u>Abbreviations:</u>

(T.L.) = type locality.
b.g.l. = below ground level.

KAINGAROA IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
344	P30238	Putunoa, near top upper sheet.	N86/918830	7.55	0.71	0.81	0.05	1122	62	46	43	415	55
345	P30240	Kaingaroa Quarry, near top of upper sheet.	N86/996721	7.70	0.41	0.76	0.09	1273	76	32	39	274	38
346	P30241	Kaingaroa Quarry, lower part of upper sheet.	N86/996721	6.58	0.55	0.94	0.03	959	65	51	50	397	69
347		Kaingaroa Forest Headquarters, basal part of upper sheet.	" "	7.16	0.39	0.68	0.07	1365	35	37	35	115	30
348	P22144	Northern Boundary Rd, upper part of lower sheet.	N86/993784	6.16	0.46	0.98	0.12	1114	70	40	45	376	52
349	P22423	Puaiti Rd, middle part, lower sheet.	N85/640737	5.86	0.71	0.47	0.66	1070	42	29	26	233	37
350	P11793	Totara Forestry Rd, near Kaingaroa H.Q., lower sheet.	N86/026709	4.79	0.87	0.54	0.24	1146	78	60	33	286	93
351		0.15 km N of Waikite Valley Rd.	N85/734799	7.53	0.37	0.52	0.08	837	48	33	21	440	74
352		Rotorua-Murupara Highway, lower sheet.	N86/020665	6.56	0.49	0.75	0.15	1344	121	68	69	223	83
353	11912	Old Waiotapu Rd, basal pumice, lower sheet.	N85/875776	4.92	0.76	0.61	0.10	1090	65	58	34	269	94
354		as above, pumice breccia 1.8 m comformably below base hard ignimbrite.	" "	4.34	0.98	0.63	0.23	1151	86	57	31	234	77
355		as above, pumice breccia 21 m below base of hard Kaingaroa Ig.	N85/875777	7.85	0.60	0.63	0.16	1543	91	72	58	255	40

MAMAKU IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
356	P30225	Drillhole 20, Kaituna Line, 83.7 m b.g.l. (sheet 1).	N67/819258	n.d.	0.01	1.43	1.48	72	6	50	1	544	37
357	P30226	as above, 101.2 m b.g.l. (sheet 1).	" "	2.02	0.02	1.22	1.54	122	4	33	44	921	38
358	P30227	as above, 117.7 m b.g.l. (sheet 2).	" "	-	-	-	-	831	47	-	54	360	-
359	P30229	as above, 150 m b.g.l. (sheet 3).	" "	8.65	0.25	0.80	0.24	1080	62	54	39	486	29
360	P30230	as above, 157 m b.g.l. (base sheet 3).	" "	7.31	0.39	0.59	0.38	991	51	55	42	627	36
361	P30231	as above, 161.6 m b.g.l. (top sheet 4).	" "	6.38	0.25	0.60	0.10	1055	68	59	28	356	50
362		Lysaght's Farm, L. Okareka, basal 10 cm (61 cm T), ash at base of Mamaku Ignimbrite.	N76/855020	7.33	0.42	0.71	0.15	1295	69	55	40	1036	55
363		as above, 2.4 m above base of ignimbrite.	" "	7.51	0.39	0.89	0.14	1216	87	44	34	691	-
364		Mamaku Plateau, Rotorua-Tirau Highway.	N76/583128	7.76	0.44	1.42	0.14	851	62	56	18	255	56
365		[a]Rotorua-Whakatane Highway, 0.3 km west Ruato.	N76/891139	8.77	0.30	1.13	0.20	833	52	47	36	1398	45
366		[a]as above, nr. Hauparu Bay.	N76/877152	8.44	0.48	1.20	0.23	734	63	55	43	449	52
367	P30238	Drillhole 20, Kaituna Line, 171 m b.g.l. - Te Akau Ig.	N67/819258	6.40	0.53	0.68	0.32	1242	73	68	30	385	40
		POKOPOKO BRECCIA											
368		Lysaght's Farm, L. Okareka, 2 m below Mamaku Ig.	N76/855020	7.24	0.42	0.68	0.12	778	59	45	20	722	47
369		as above, 7.6 m below Mamaku Ig.	" "	8.31	0.49	0.66	0.14	989	82	51	30	191	46
370		Miller Rd, L. Okareka	N76/810003	7.01	0.34	0.61	0.17	1066	71	49	35	286	71
371		L. Okareka, Nairns backyard.	N76/806001	5.90	0.75	0.84	0.13	1175	58	58	25	319	24

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
			MATAHINA IGNIMBRITE										
372	P31373	Drillhole 72, Matahina Dam Site, 23.5 m b.g.l.	N77/258064	6.48	0.39	0.67	0.13	1322	39	39	33	140	44
373	P31379	as above, 46.6 m b.g.l.	" "	8.08	0.41	1.03	0.11	1070	54	41	22	149	36
374	P31381	" " 64.6 m b.g.l.	" "	7.92	0.42	0.95	0.12	1299	43	41	27	195	35
375	P31386	" " 111.6 m b.g.l.	" "	7.87	0.39	0.68	0.12	1342	34	30	28	93	-
376	P31391	" " 137.2 m b.g.l.	" "	7.91	0.48	0.66	0.26	1436	43	41	24	264	-
377		[b]L. Rotomahana.	N86/905875	5.18	0.52	0.91	0.17	1035	86	57	48	310	70
378		[b]L. Rotomahana, ash at base of ignimbrite.	N86/905877	5.62	0.73	0.70	0.15	1302	84	63	31	115	35
379		[b]Anaputa Point, L. Rotoma.	N77/038166	4.37	0.56	0.67	0.34	1143	54	50	22	190	44
381	30022	Matahina Damsite.	N77/256062	7.34	0.49	0.93	0.07	1241	168	40	473	313	54
382	11913	Kiorenui Forestry Rd, near Murupara, upper pumice breccia.	N86/138659	7.01	0.53	0.66	0.11	939	45	47	37	307	68
			ATIAMURI IGNIMBRITE										
383	P30507	Atiamuri-Wairakei Highway, 0.5 km S of Mawson Rd, 3.05 m above base.	N85/534687	5.26	0.38	0.63	0.06	715	25	70	18	363	22
384	P30508	as above, 6.1 m above base.	" "	5.15	0.32	0.64	0.04	669	49	32	18	463	20
385	P30509	as above, 9.1 m " "	" "	4.80	0.34	0.64	0.04	641	20	41	17	264	17
386	P23846	S side Waikato River.	N85/624608	5.90	0.41	0.80	0.06	796	33	38	24	356	38
387	P22457	Rogerson Rd.	N84/443674	5.67	0.44	0.47	0.05	2283	124	59	80	128	32
			ORAKONUI PUMICE BRECCIA										
388	P24750	0.4 km S of Tutukau Rd.	N94/577581	5.43	0.47	0.56	0.14	1290	31	59	38	802	35
			HUKA PUMICE BRECCIA										
389	P24704	0.4 km S Rawhiti Rd.	N85/859635	7.37	0.66	1.08	0.06	2529	128	108	88	185	52
			MOKAI IGNIMBRITE										
390		[c]Marotiti Rd.	N93/361586	6.41	0.35	0.81	0.12	1105	56	51	23	356	40

RANGITAIKI IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
391	P30382	Rangitaiki deep hole, No. 3, 33.5 m b.g.l.	N103/370175	7.24	0.82	0.56	0.71	2848	217	84	99	118	42
392	P30384	as above, 84 m b.g.l.	" "	7.10	0.80	0.60	0.60	3070	235	89	103	172	25
393	P30386	as above, 82.3 m b.g.l.	" "	8.53	0.76	0.57	0.83	3137	223	84	111	194	40
394	P30383	as above, 111.3 m b.g.l.	" "	7.59	0.67	0.60	0.93	3410	243	85	113	313	35
395	P30389	as above, 126.5 m b.g.l.	" "	5.37	0.82	0.36	0.91	3057	183	88	103	319	68
396		^cTe Toki Point, L. Taupo	N103/466147	7.32	0.74	0.58	0.89	2480	227	84	183	139	33
397		as above, 3 m above road level.	" "	6.62	0.63	0.56	0.95	2587	260	79	169	254	35
398		Rotorua-Murupara Highway.	N86/126658	5.52	0.56	0.59	0.20	2839	203	83	85	193	72
399		Torepatutahi Stream (T.L.)	N85/853608	5.38	0.73	0.51	0.40	2599	240	75	111	153	67
			WAIRAKEI IGNIMBRITE										
400	P33892	Wairakei Drillhole 227, 914.4 - 916 m b.g.l.	N94/593443	5.93	0.81	0.57	1.26	2616	185	94	98	224	91
401	P33899	as above, 1082 - 1083.6 m b.g.l.	" "	5.85	1.72	0.45	2.07	2711	476	86	151	155	62

T E W H A I T I I G N I M B R I T E

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
402	P29372	Hole 21, left bank of Rangitaiki River, 4.6 m b.g.l.	N95/102546	5.30	0.71	0.67	0.38	2138	208	86	87	321	80
403	P29373	as above, 19.2 m b.g.l.	" "	6.16	0.66	0.75	0.58	2159	218	97	76	532	57
404	P29374	as above, 22.6 m b.g.l.	" "	7.01	0.77	0.83	0.73	2401	269	70	78	544	67
405	P29375	as above, 25.3 m b.g.l.	" "	6.38	0.66	0.74	0.51	2423	247	63	88	404	45
406	P29376	as above, 28 m b.g.l.	" "	6.68	0.70	0.71	0.53	2548	244	78	81	427	33
407	P29378	as above, 42.7 m b.g.l.	" "	7.71	0.71	0.73	0.69	2680	239	70	86	332	23
408	P29382	Hole 36, right bank of Rangitaiki River, 34.4 m b.g.l.	N95/110541	6.70	0.74	0.72	0.61	2441	241	68	75	298	45
409	P29384	as above, 96.3 m b.g.l.	" "	7.37	0.90	0.50	1.10	3077	228	75	99	341	34
410		[d]Poutu Tunnel, Tongariro Power Project at 1615 m.		7.33	0.82	0.98	0.69	1977	256	62	70	246	70
411		Ash under ignimbrite, Poutu Tunnel.		5.21	0.54	0.44	1.02	2906	184	99	102	402	-

M A N U N U I I G N I M B R I T E

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
412	10781	Arapuni Damsite	N75/138131	6.11	0.76	0.38	0.27	2603	221	97	119	92	43
413	P27579	Nr. Arapuni Power House.	N75/137127	6.01	0.56	0.41	0.23	3541	228	129	120	52	26
414		[c]0.2 km SW of Dukesons Rd, turnoff.	N75/223124	6.22	0.36	0.54	0.07	2612	142	65	74	148	48
415		Mangakahu Rd (type area).	N92/887308	5.74	0.56	0.41	0.20	3428	219	114	140	100	29

WHAKAMARU IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
416	P20116	Waipapa Damsite, drillhole 1, 3.3 m above base sheet 1.	N84/176846	6.26	0.85	0.40	0.50	2937	203	92	94	275	63
417	P20115	as above, 3.7 m above base sheet 1.	" "	7.75	1.21	0.50	0.97	3091	270	97	116	163	-
418	P20112	as above, 25.9 m above base sheet 1.	" "	6.88	0.87	0.51	1.10	3183	294	78	93	262	-
419	P20111	as above, 70.1 m above base sheet 1.	" "	7.43	1.06	0.76	1.51	2023	201	63	60	297	41
420	P27835	as above, crystal tuff at base sheet 2.	" "	6.59	0.76	0.46	0.24	3096	218	98	113	355	63
421	P27834	as above, within 1.5 m of base of sheet 2.	" "	5.96	0.72	0.49	0.27	2325	185	90	103	407	42
422		Waipapa Damsite mod. welded part mid. sheet, 146.3 m above sea level.	N84/175845	5.80	0.63	0.64	0.09	2520	206	86	82	292	38
423		Waipapa Damsite, 30.5 m above base, top sheet, 198.1 m above sea level.	N84/169857	6.10	0.64	0.73	0.48	2081	205	72	87	321	70
424		Waipapa Damsite, top, top sheet, non-welded 259 m above sea level.	N84/166855	6.79	0.66	0.74	0.11	2070	248	70	88	382	77
425		Waipapa-Arapuni Highway, soft pink pumice breccia.	N84/162887	6.06	0.47	0.69	0.15	3107	238	88	96	454	32
426		[c]Whakamaru Damsite, drillhole 139, 53 m b.g.l.	N84/294702	4.94	0.41	0.60	0.16	2796	183	75	95	101	43
427		Ranginui Road.	N84/121717	5.95	0.43	0.63	0.19	2499	197	82	94	436	40
428		Maraetai-Waipapa Highway, ash at base sheet 2.	N84/192787	5.78	0.61	0.51	0.29	3341	221	104	107	252	26
429		Scott Rd, soft pink pumice breccia.	N84/150688	6.13	0.55	0.81	0.19	2937	239	99	97	587	63
430		Okauaka Rd, soft pink pumice breccia.	N92/915479	5.20	0.41	0.67	0.21	2521	170	77	83	500	74
431		Maraetai-Waipapa Highway, ash 1.3 m under Whakamaru Ig.	N84/192787	6.56	0.75	0.74	0.15	3308	183	113	97	124	38

PAEROA IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
432		Paeroa Range (T.L.)	N85/740767	4.89	0.42	0.84	0.28	1431	101	50	35	301	57
433	P34906	0.15 km west of Trig. Wharepapa No. 2.	N85/750740	5.63	0.78	0.81	0.11	1704	132	85	30	-	-
434	10785	Paeroa Range, upper part, lowest sheet.	N85/722747	6.02	0.32	0.64	0.10	2279	166	90	68	164	55
435		Ngapouri Ridge, top sheet.	N85/792777	5.55	0.65	0.90	0.12	1500	109	67	76	185	-
436		Paeroa Range.	N85/748777	5.38	0.45	0.92	0.13	2497	175	64	59	283	37
			TE WETA IGNIMBRITE										
437		^{b}Paeroa Range.	N85/720755	5.51	0.68	0.64	0.37	1584	96	45	98	180	79
438		Paeroa Range.	N85/723754	5.80	0.49	0.62	0.12	1822	111	49	56	112	35
439		Quarry at foot of Paeroa Range.	N85/716748	4.45	0.49	0.87	0.10	1864	116	45	49	96	52
440		^{b}Paeroa Range.	N85/738768	4.75	0.31	0.73	0.09	1737	109	36	38	79	74
441		^{b} " "	N85/717745	3.91	0.42	0.89	0.10	1482	80	33	28	171	55
			TE KOPIA IGNIMBRITE										
442	P22444	Paeroa Range.	N85/736769	5.60	0.62	0.62	0.15	3134	231	108	107	100	36
443	P22447	" "	" "	4.96	0.64	0.52	0.17	2992	200	113	119	107	65
444	P22443	" "	" "	4.88	0.55	0.48	0.24	2893	188	118	118	81	49
445	P22445	" "	" "	5.52	0.47	0.49	0.14	3378	200	103	109	71	25
446		^{b} " "	N85/736768	5.67	0.55	0.44	0.10	3382	182	87	108	96	93
447		" "	N85/736765	5.73	0.62	0.46	0.13	4016	199	106	106	84	54
448		^{b}NE end Paeroa Range.	N85/758798	5.45	0.52	0.36	0.42	3377	174	84	96	91	86
449	✓ 11914	^{b}2.2 km east of Paeroa Range scarp.	N85/763763	6.21	0.57	0.48	0.13	3680	203	100	106	124	60

WAIOTAPU IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
450		Pine Rd.	N85/525838	7.66	0.38	1.26	0.12	1000	45	41	30	475	32
451	10790	2.3 km NW of Pine Rd, highly welded pink lenticulite.	N85/515860	8.81	0.52	0.82	0.13	1603	71	86	50	578	27
452		[c]Amos Farm Well, Kinleith Bore, 57, 45.7 m b.g.l.	N75/377902	9.17	0.39	0.97	0.22	1111	47	46	31	445	37
453		[c]as above, 66.8 m b.g.l.	" "	8.76	0.43	0.74	0.56	1480	60	51	49	301	33
454	30001	Putaruru Lichfield Quarry, 1 m due E of Lichfield.	N75/336077	8.00	0.45	1.09	0.04	1881	90	91	61	169	57
455		0.9 km N of Waikite Valley Rd.	N85/704789	7.67	0.22	0.87	0.09	772	58	28	40	143	42
456		[b]1.6 km W of Rotorua-Taupo Highway (type area).	N85/796764	6.83	0.37	0.61	0.06	1524	92	48	36	131	98
457		[b]Whirinaki , 0.9 km W of Corbett Rd.	N85/717843	7.76	0.34	0 .76	0.07	1371	59	42	32	101	47
			MARSHALL IGNIMBRITE										
458	10779	Mangakino-Waipapa Rd, (Taupaki member).	N84/196785	11.19	0.22	2.61	0.13	1042	83	65	48	630	43
459	10780	3.8 km E of Waikato River, lowermost lenticulite member.	N84/214895	13.33	0.51	1.02	0.18	1124	88	67	56	889	74
460		[c]Mangakino-Waipapa Rd, unconformably under Whakamaru Ig.	N84/201781	12.01	0.23	1.85	0.18	1033	93	98	47	476	57
461		as above	N84/201782	8.92	0.19	1.45	0.10	957	73	61	29	250	42
			OHAKURI PUMICE BRECCIAS										
462	P22074	Ngakuru, 0.1 km N of Trig 671.	N85/640830	6.64	0.44	0.64	0.10	1492	45	65	51	120	54
463	P22433	Ohakuri Rd.	N85/542715	6.65	0.44	0.98	0.05	1506	45	108	53	496	46
464	P22433B	" "	" "	6.52	0.52	0.82	0.05	1685	45	75	56	175	44
465	P30916	Puaiti Rd, 0.1 km W of Trig 1778.	N85/643735	6.23	0.48	0.65	0.08	1376	41	60	43	102	33
466	P30917	Galatos Rd.	N85/612784	6.71	0.51	0.67	0.12	1592	48	55	51	257	35
467	P30918	0.2 km N of Galatos Rd.	N85/610787	6.39	0.51	0.65	0.12	1455	41	66	42	153	26

ROCKY HILL IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
468	10782	SW of Arapuni, 0.7 km W of Waikato River.	N75/120105	6.01	0.41	0.46	0.11	2703	213	69	72	187	112
469	11917	Okauaka Rd - hard lenticulite upper unit.	N92/940471	5.70	0.67	0.59	0.75	2513	251	84	82	139	68
470		Tauwrimu Homestead end Gardiners Rd.	N83/846715	7.40	0.24	0.23	0.14	2545	298	51	78	888	105
471		Ellis Rd, by Maraeroa Rd, turnoff, ignimbrite on ash.	N93/026588	5.71	0.56	0.44	0.15	3239	216	94	103	116	36
472	11915	as above, ash under ignimbrite.	" "	6.19	0.64	0.45	0.16	3515	220	100	112	416	40
473		Waimahora Rd, middle, lower sheet.	N83/943803	6.01	0.40	0.54	0.16	2500	199	65	74	217	41
474	11916	as above, basal 6 m lower sheet.	N83/944803	10.41	0.33	0.12	1.02	994	93	49	34	648	109
475		as above, 22.9 m above base.	" "	8.58	0.33	0.11	0.57	920	129	-	-	456	113

AHUROA IGNIMBRITE

upper and middle sheets

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
476		^{c}0.1 km N, Arapuni Damsite.	N75/135114	13.84	0.56	0.80	0.19	411	30	47	32	288	61
477	10792	Waipapa Damsite, Bore 163 depth 46.9 m		8.28	0.20	0.89	0.13	1053	81	46	34	325	82
478		Gardiners Rd.	N83/836737	10.61	0.27	1.03	0.16	537	57	42	20	276	66
479		W side Arapuni Dam.	N75/132114	10.23	0.30	0.90	0.21	1019	85	55	48	1043	70
480		Kahorekau Rd, 1.4 km before Taupaki Rd junction.	N75/096968	12.16	0.44	0.72	0.17	462	49	48	22	525	63
481	11919	Tiroa Pa, tor near Barryville, pumice breccia, base of tor.	N92/964592	11.56	0.40	1.27	0.17	665	69	63	28	286	64
482		as above, fibrous pumice above pumice breccia.	" "	11.96	0.23	1.37	0.16	364	70	67	22	1257	88
483	11920	as above, lenticulite capping tor.	" "	11.78	0.26	1.10	0.19	573	63	75	26	239	76
484	11918	Waipapa-Arapuni Highway, 3.7 m from base of 9.1 m tuffs.	N84/157887	12.08	0.32	0.93	0.19	835	72	60	40	705	83

lower sheet

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
485		Gardiners Rd, pumice lenticulite 1.7 km past Lands & Survey Station.	N83/831739	7.53	0.57	0.51	0.18	3173	281	83	100	114	71
486	11921	Waipapa-Arapuni Highway, 1.5 km N of Mangawhio Bridge, (pumice breccia).	N84/157887	7.57	0.49	0.60	0.15	3158	214	142	106	126	56
487		as above, ash immediately overlying pumice breccia.	" "	7.27	0.35	0.53	0.06	3021	176	147	89	205	56

WAIPARI IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
488		Ngaroma Rd, pumice breccia near top of top sheet.	N75/052918	6.39	0.37	0.58	0.14	2803	176	83	84	102	28
489		as above.	N75/024952	6.70	0.45	0.51	0.15	2863	173	89	93	134	36
490	11928	as above, near top of top sheet - pumice breccia.	N75/047928	7.27	0.44	0.43	0.23	3124	157	80	98	100	39
491	11922	as above, by bridge basal sheet.	N75/013963	6.56	0.53	0.47	0.27	2887	179	83	89	76	52
			ONGATITI IGNIMBRITE										
493		[c]Ongarue-Waimihia Rd.	N92/808431	7.67	0.32	0.45	0.25	2434	161	77	92	90	32
494	10783	2.5 km SW Arapuni, W side Arapuni Lake.	N75/120105	6.04	0.44	0.50	0.14	2735	197	79	101	272	87
495		Aria-Waimihia Highway.	N92/807460	6.91	0.38	0.47	0.10	2847	164	79	79	60	31
496	11923	0.2 km before Ongarue Stream Rd turnoff.	N92/827470	7.20	0.35	0.46	0.32	2875	185	75	107	112	57
497		Owawenga Rd.	N83/880829	6.90	0.54	0.46	0.16	2840	176	84	97	116	43
498		Waipa River Rd.	N83/854873	6.49	0.43	0.47	0.10	2814	172	77	86	48	25
499		Mapara North Rd.	N83/704618	6.89	0.22	0.43	0.11	3215	206	63	106	57	50
500		Mapara North Rd, basal 1 m on siltstone.	N83/717613	7.68	0.48	0.50	0.14	3207	182	79	106	84	53
501		as above, 6 m above base.	" "	7.51	0.52	0.51	0.17	3342	200	85	108	92	41
502		[c]Dukesons Rd, 4.5 km SW of Putaruru.	N75/223124	6.22	0.26	0.54	0.08	2613	141	59	74	148	48
503		S side Waipapa River.	N84/117725	7.13	0.35	0.61	0.17	2983	203	83	96	93	38

RANGITOTO IGNIMBRITES

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
Crystal Lithic - Lapilli Ignimbrite													
504		Ngaroma Mill Rd, 0.6 km from mill.	N84/062816	9.39	0.33	0.58	0.12	1369	217	58	54	259	106
505	11924	as above, 0.7 km from mill.	N84/062815	10.23	0.35	0.71	0.18	1318	146	66	50	213	61
506		Tolley Rd.	N84/041823	11.33	0.30	0.50	0.17	1722	157	70	59	254	75
507		Ngaroma Mill Rd.	N84/051753	9.62	0.41	0.69	0.17	1479	139	68	50	189	51
Ranginui Ignimbrite (previously tentatively correlated with Ngaroma Lenticulite)													
508	11925	Ranginui Rd.	N84/123721	11.36	0.32	1.15	0.19	469	67	72	38	261	72
509		^{c}Waipapa-Arapuni Highway (not in place).	N84/157887	10.91	0.49	1.04	0.16	613	55	70	44	228	56
Ngaroma Lenticulite													
510		Ngaroma Mill Rd.	N84/742049	6.79	0.51	0.49	0.30	3119	167	84	84	110	36
511	11926	" "	N84/050729	7.61	0.33	0.56	0.08	2497	155	66	82	81	64
512		Ahuroa Rd.	N83/762777	11.31	0.72	0.33	0.19	31274	1453	105	330	215	150
Pumice - Lapilli Ignimbrite													
513	11927	Ngaroma Mill Rd, 1.5 m above base.	N84/054758	10.59	0.84	0.58	0.17	4205	401	106	175	215	62
514		as above, basal ash resting on greywacke.	" "	10.94	1.20	0.39	0.16	4953	381	147	202	641	80

WAITEARIKI IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
515	P25709	Waitcariki Stream, at level of pump house inlet, very close to inlet.	N57/367519	7.51	0.48	0.34	0.20	6858	534	146	266	141	106
516	P25707	Waitcariki Stream, above pump house inlet by 1.5 m.	N57/368518	7.84	0.37	0.26	0.31	5212	630	94	185	153	121
517	P25705	as above, by 47.2 m (halfway down main waterfall).	N57/370518	5.98	0.40	0.32	0.22	4698	449	99	191	108	56
518	P25703	as above, by 163.1 m.	N57/371516	6.64	0.41	0.38	0.19	4766	489	95	166	79	48
519	P25701	as above, by 193.5 m.	N57/371513	6.76	0.32	0.29	0.16	4362	489	100	196	104	60
520		Kaimai Railway Deviation, eastern portal, drillhole ES-106, 28.3 m b.g.l. (in well compacted lenticulite).	N57/400615	6.00	0.32	0.48	0.17	4137	419	85	156	169	65
521		as above 144.2 m b.g.l. (in hard welded lenticulite).	" "	6.44	0.45	0.27	0.24	5137	476	85	196	96	40
522		as above drillhole ES-107, 29.3 m b.g.l. (poorly compacted pumice breccia).	N57/404617	5.64	0.29	0.37	0.13	4331	457	82	151	138	77
523		as above, 59.7 m b.g.l. (in well compacted lenticulite).	" "	5.82	0.35	0.43	0.15	4022	493	94	160	124	71
524		as above, drillhole ES-105, 59.7 m b.g.l. (hard welded lenticulite).	N57/397613	6.81	0.49	0.29	0.65	4821	383	92	156	290	86
525		as above, drillhole ES-103, 60.4 m b.g.l.	N57/394611	6.80	0.54	0.29	0.76	4520	355	96	166	394	92

PAPAMOA IGNIMBRITE

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
526		Rocky Cutting Rd.	N58/723546	8.86	0.67	0.43	0.13	4899	267	94	150	93	39
527		0.8 km W, Reids Rd, turnoff.	N58/738552	6.75	0.56	0.35	0.14	5191	531	84	177	108	109

AONGATETE VOLCANICS

Upper Tuffs and Breccias.

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
528		Kaimai Railway Deviation, east portal, drillhole ES-104, 75 m b.g.l.	N57/396612	7.56	0.92	0.46	0.16	5561	1708	324	334	98	176
529		as above, ES-107, 151.5 - 152 m b.g.l.	N57/404617	9.58	0.64	0.32	0.55	4904	1498	240	251	236	149

Aongatete Ignimbrite

ANALYSIS No.	SAMPLE No.	LOCATION	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
530		as above, ES-101, 201.2 m b.g.l., (moderate - well compacted pumiceous breccia).	N57/388607	7.67	1.97	0.35	0.49	1404	226	63	79	167	82
531	11929	as above, ES-104, 213.4 m b.g.l., (as above).	N57/396612	6.69	1.19	0.38	0.69	1211	335	76	51	227	72
532		as above, ES-106, 210.3 m " (as above).	N57/400615	9.54	0.73	0.46	0.70	1182	226	99	107	153	94
533		as above ES-102, 147.5 m " (hard lenticulite).	N57/392609	10.90	0.48	0.68	0.19	1277	104	86	102	375	92
534		as above, ES-101, 143 m " (hard lenticulite).	N57/388607	9.76	0.58	0.33	0.44	1035	104	47	50	201	126
535		as above, ES-100, 99.4 m " (hard lenticulite).	N57/385606	9.16	1.86	0.41	0.99	1696	345	78	68	154	89
536		as above, ES-103, 141.1 m " (hard lenticulite).	N57/394611	11.97	0.92	0.49	0.38	1060	133	69	126	564	82

ANALYSIS No.	SAMPLE No.	L O C A T I O N	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
537		as above, ES-100, 197.5 m b.g.l. (hard welded lenticulite).	N57/385606	11.26	1.87	0.27	0.84	1846	305	60	98	279	118
538		as above, ES-101, 237.4 m " (hard welded lenticulite).	N57/388607	9.31	1.16	0.28	0.65	1498	219	66	98	153	120

'T R I D Y M I T E   R H Y O L I T E'

ANALYSIS No.	SAMPLE No.	L O C A T I O N	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
539		Waikino Quarry, 19.8 m above base.	N53/274923	10.83	0.31	0.37	0.20	453	51	152	326	312	174
540	P29265	" " 16.2 m above base.	" "	9.87	0.28	0.38	0.17	314	72	-	-	60	-
541	P29264	" " 5.6 m above base.	" "	9.72	0.29	0.29	0.33	546	61	72	279	102	-
542	P29250	" " 4.4 m above base.	" "	11.28	0.20	0.20	0.73	866	71	78	118	285	-

W I L S O N I T E   (O W H A R O A I T E)

ANALYSIS No.	SAMPLE No.	L O C A T I O N	GRID REFERENCE	Ti%	Mg%	Mn%	Ca%	V	Cr	Co	Ni	Zr	Cu
543	10784	Waikino Ig. - Owharoa Quarry, glassy lenticulite.	N53/255917	8.96	0.43	0.29	0.14	3524	311	79	124	227	46
544		Owharoa Quarry.	N53/257919	8.12	0.38	0.28	0.09	3557	419	78	162	109	63
545	P29253	" " 37.8 m above base of section.	" "	7.24	0.33	0.28	0.11	3447	409	90	158	130	79
546	P29254	as above, 1.8 m above P29253.	" "	7.38	0.29	0.23	0.16	3374	295	92	145	93	116
547	P29255	as above, 1.8 m above P29254	" "	7.83	0.30	0.32	0.10	3923	565	115	172	124	104

APPENDIX VI

NEW ZEALAND BIBLIOGRAPHY OF QUATERNARY TEPHROCHRONOLOGY

Compiled as part of the World Bibliography on Quaternary Tephrochronology to be presented by the Commission on Tephrochronology at the INQUA Conference, Christchurch, December 1973.
References included are up to December 1970.

Introductory Statement:

Many references to historic eruptions in which tephra was erupted have not been listed. For bibliographies and information about these eruptions see:-

(1) For 1886 Tarawera Eruption - Thomas 1888 and Cole 1970b (contains an appendix with a bibliography of papers written about the Tarawera Eruption of 10 June 1886).

(2) For activity from Mts. Ruapehu, Tongariro and Ngauruhoe - Gregg 1960 a & b (contains tables summarising activity and a detailed list of references accompanying each reported eruption).

(3) For activity from White Island - see Luke 1959, Baumgart 1959, Healy 1967b, Duncan and Vucetich 1970.

Thomson 1926 summarises all historical eruptions in New Zealand up to 1926.

For stratigraphic names and descriptions of New Zealand Quaternary pyroclastic rocks see Fleming 1959. Fleming 1959 and Adkin 1954 list references in which the names and descriptions are proposed or used.

University theses have only been listed where all or part of them were unpublished at December 1970.

The words (esp.) with~~ page numb~~ers, following any listed reference, indicate pages of tephrochronological interest within publications containing many pages.

References are grouped into the categories:

Group A = basic problems on tephrochronology.
A(i) = principles, methods and dating.
A(ii) = recent volcanic activity (see above statement).
A(iii) = applications of tephrochronology (e.g. to soil science, clay mineralogy, archaeology and palynology).

Group B = regional tephrochronology.

Explanation of abbreviations:

Amer. Geophys. Un. Geophys. Monogr. - American Geophysical Union, Geophysical Monograph.

Bull. Volc. - Bulletin Volcanologique.

Earth Pl. Sci. Letters - Earth and Planetary Science Letters.

Earth Sci. J. - Earth Science Journal.

Geochim. Cosmochim. Acta - Geochimica et Cosmochimica Acta.

Hist. Rev., J. Whakatane Dist. Hist. Soc. - Historical Review, Journal of the Whakatane and District Historical Society Inc. N.Z.

J. Hyd. (N.Z.) - Journal of Hydrology (N.Z. Hydrological Society).

J. Petrol. - Journal of Petrology.

J. Polynes. Soc. - Journal of the Polynesian Society.

J. Soil Sci. - Journal of Soil Science.

Min. Mag. - Mineralogical Magazine.

N.Z. Arch. Assn. - Newsletter - New Zealand Archaeological Association - Newsletter.

N.Z.D.S.I.R. Annu. Rept. - New Zealand Department of Scientific and Industrial Research Annual Report.

N.Z.D.S.I.R. Bull. - New Zealand Department of Scientific and Industrial Research Bulletin.

N.Z.D.S.I.R. Inf. Ser. - New Zealand Department of Scientific and Industrial Research Information Series.

N.Z. Geogr. - New Zealand Geographer.

N.Z. Geol. Surv. Annu. Rept. - New Zealand Geological Survey Annual Report.

N.Z. Geol. Surv. Bull. n.s. - New Zealand Geological Survey Bulletin new series.

N.Z. Geol. Surv. Mem. - New Zealand Geological Survey Memoir.

N.Z.J. Ag. - New Zealand Journal of Agriculture.

N.Z.J. Ag. Res. - New Zealand Journal of Agricultural Research.

N.Z.J. Bot. - New Zealand Journal of Botany.

N.Z.J. For. - New Zealand Journal of Forestry.

N.Z.J. Geol. Geophy. - New Zealand Journal of Geology and Geophysics.

N.Z.J. Sci. - New Zealand Journal of Science.

N.Z.J. Sci. Tech. - New Zealand Journal of Science and Technology.

N.Z. Sci. Rev. - New Zealand Science Review.

N.Z. Soc. Soil Sci. Proc. - New Zealand Society of Soil Science Proceedings.

N.Z. Soil Bur. Bull. - New Zealand Soil Bureau Bulletin.

N.Z. Soil Bur. Rept. - New Zealand Soil Bureau Report

Proc. Conf. N.Z. Grasslands Assoc. - Proceedings of the Conference of the New Zealand Grasslands Association.

Proc. N.Z. Ecol. Soc. - Proceedings of the New Zealand Ecological Society.

Proc. N.Z. Geogr. Conf. - Proceedings of the New Zealand Geographers Conference.

Proc. N.Z. Sci. Congr. - Proceedings of the New Zealand Science Congress.

Proc. Pac. Sci. Congr. - Proceedings of the Pacific Science Congress.

Quat. Soils Proc. - Quaternary Soils Proceedings

Rec. Auck. Inst. Mus. - Records of the Auckland Institute and Museum.

Rept. Annu. Meet. N.Z. Ecol. Soc. - Report of the Annual Meeting of the New Zealand Ecological Society.

Rept. Annu. Meet. N.Z. Geol. Soc. - Report of the Annual Meeting of the New Zealand Geological Society.

Trans. N.Z. Inst. - Transactions of the New Zealand Institute.

Trans. R. Soc. N.Z. - Transactions of the Royal Society of New Zealand.

GROUP A

Category A(i)

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- eruptions (see eruptive history).

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